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HIGH PRESSURE BURNING RATES OF MULTI-BASE PROPELLANTS

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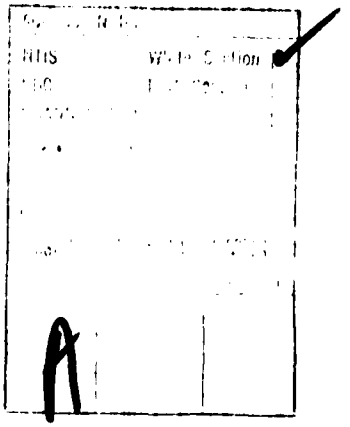
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Burning rates of multi-base, nitrocellulose propellants at high pressure were measured using recently developed techniques. Since the intended application is in-process control, as-manufactured multi-perforated grains (finished as well as interrupted-process propellants) are used. Chamber pressurization to 345 MPa (50,000 psi) is achieved using a hydraulic pump, rather than by nitrogen intensifier systems; the burning interval is determined by timing either the period of acoustic emission or pressure rise. Burning

19. Abstract - continued

rate data for several lots of M1, M26, M30, and HMX polyurethane propellants are presented. Burning rate consistency of M26 double-base propellant is good, i.e., coefficient of variation ≈ 1%. However, the burning rate variability of single base propellants is dependent on the dispersion of fibrous nitrocellulose. Burning rate exponents obtained under steady state burning conditions are about 20% higher than recent closed chamber results. The results from a large number of specimens tested during the study demonstrate that the apparatus and data analysis techniques can be efficiently used under production situations.

Preface

This project conducted under U.S. Army Contract DAAA21-76-C-0230 and is part of the U.S. Army's project to modernize the manufacture and acceptance of multi-base propellants. The technical monitors were Messrs. F. J. Fitzsimmons, P. A. Serao, and J. K. Domen of the Product Assurance Directorate (SARPA-QA-A-P). Their technical involvement significantly aided this project.



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1.0 INTRODUCTION

Accurate and rapid determinations of burning irregularities and burning rates are important in the characterization and in-process quality control of multi-base nitrocellulose propellants manufactured by modernized processes. However, the test procedures currently available to provide these data are cumbersome to implement and at high pressures (> 69 MPa, 10,000 psi) do not yield sufficient information to resolve the burning rate variations of individual grains which result from small changes in propellant formulation and processing procedures.

This study refined and applied the experimental approach for measuring burning rates which was developed under Contract DAAA21-74-C-0332 (see Ref. 1). This new approach departs from the conventional methods of chamber pressurization and burning interval measurement. Chamber pressurization to 345 MPa (50,000 psi) is achieved with a hydraulic pump, rather than the expensive and temperamental nitrogen intensifier systems; the burning interval is monitored automatically by timing either the period of acoustic emission from the burning propellant or the period of pressure rise, rather than by fuse wire schemes which are unsatisfactory for small propellant specimens. The technique of using the period of acoustic emission originated at the Air Force Rocket Propulsion Laboratory[2] and has been used effectively for rocket propellants at pressures below 10 MPa (1500 psi). Furthermore, an important advantage of the technique (summarized in Ref. 1) is its ability to measure rapidly burning rate irregularities and burning rates of the grains taken directly from production lines and, thereby, to determine rapidly compliance with specifications so that process adjustments can be made within a fraction of an hour, if necessary.

The specific objectives of the study summarized in this report include: (1) to refine and apply techniques for rapidly measuring the burning rates of as-manufactured grains, e.g., small multi-perforated grains, (2) to achieve accurate burning rate measurements [e.g., a coefficient of variation (cov) of

1%], (3) to measure the burning rates of several types of nitrocellulose-base propellants (in particular, M26 and M30), (4) to measure lot-to-lot variations of production propellants, and (5) to describe the approach so that it can be used by other laboratories.

2.0 EXPERIMENTAL APPROACH

2.1 Apparatus for Measuring Burning Rate*

A high-pressure (up to 345 MPa, 50,000 psi) apparatus was developed in which the primary observables during a test are: (1) ultrahigh frequency acoustic emission (UHFAE) generated by the combustion proce..; [2-4] and (2) very small pressure fluctuations, which are a direct consequence of burning propellants in a hydraulic medium with a very small free gas volume. From either of these observables, the burning rate can be obtained. This study employs the apparatus to focus on the combustion of nitrocellulose-base solid propellants in the form of as-manufactured, multi-perforated grains. The major sub-assemblies of the high-pressure apparatus include an air-actuated high-pressure hydraulic pump, a liquid-filled (usually water) combustor cell, the UHFAE data acquisition system (e.g., Dunegan/Endevco AE 4001 amplifier, 802P-A preamplifier, and 731 transducer), and the pressure rise data acquisition system (e.g., Kistler 607C4 piezoelectric pressure transducer and 504A charge amplifier).

The arrangement of the heavy-walled combustor and an air-actuated high-pressure hydraulic pump is shown in Fig. 2-1. The heavy-walled combustor with a single (large) grain and a hot-wire igniter in position is shown in Fig. 2-2. The dimensions of the combustor are shown in Fig. 2-3. Photographs of the pump console and combustor are shown in Fig. 2-4. A special fixture used to ignite the top surfaces of a multi-perforated grain is shown in Fig. 2-5.

The combustion-generated UHFAE sensed by an acoustic transducer and the pressure rise sensed by the piezoelectric pressure transducer are processed as shown in Fig. 2-6. The acoustic transducer output is filtered and frequency components above 100 kHz are preamplified 1000 times (60 dB) and then

*This section contains a reasonably detailed description of the apparatus, instrumentation, and test procedure. Step-by-step details of the operating procedures, check lists, and design requirements are placed in the Appendices.

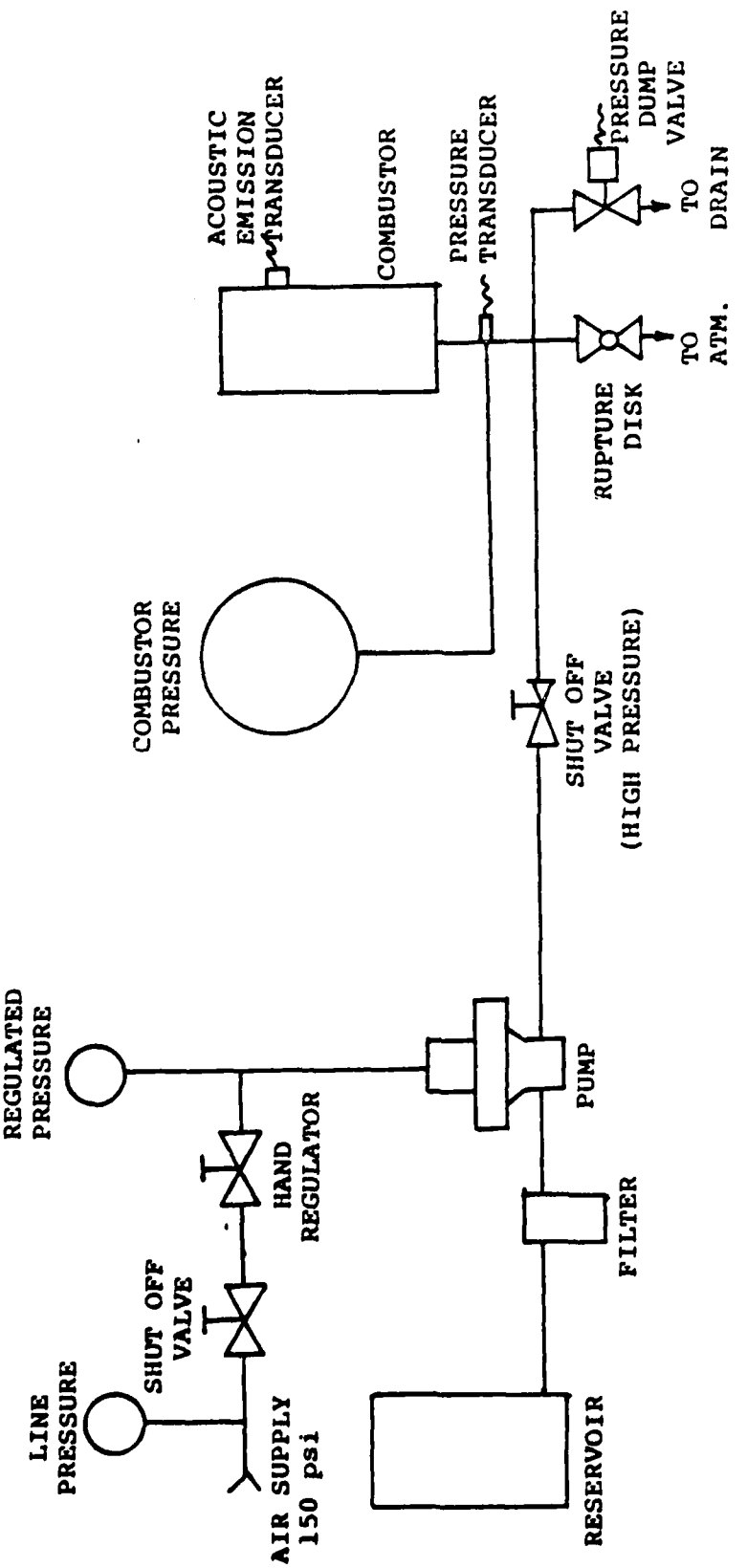


Fig. 2-1 Hydraulic system used to pressurize high-pressure combustor.

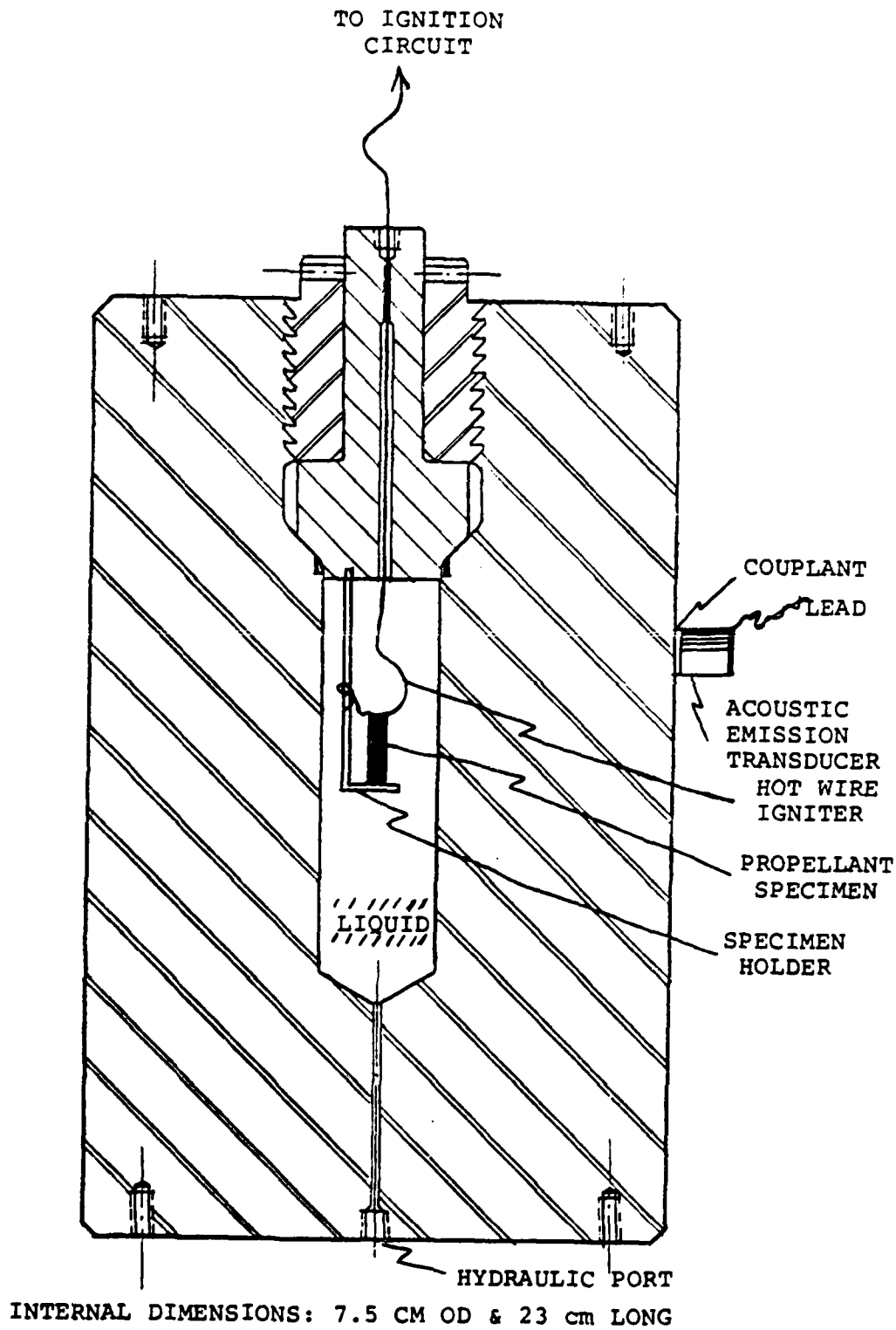


Fig. 2-2 Schematic drawing of combustor system showing arrangement of igniter, propellant sample, and acoustic emission detector.

SCALE = 1 to 4
OPERATING PRESSURE: 50,000 PSI (345 MPa)
DESIGN PRESSURE: 100,000 PSI (690 MPa)

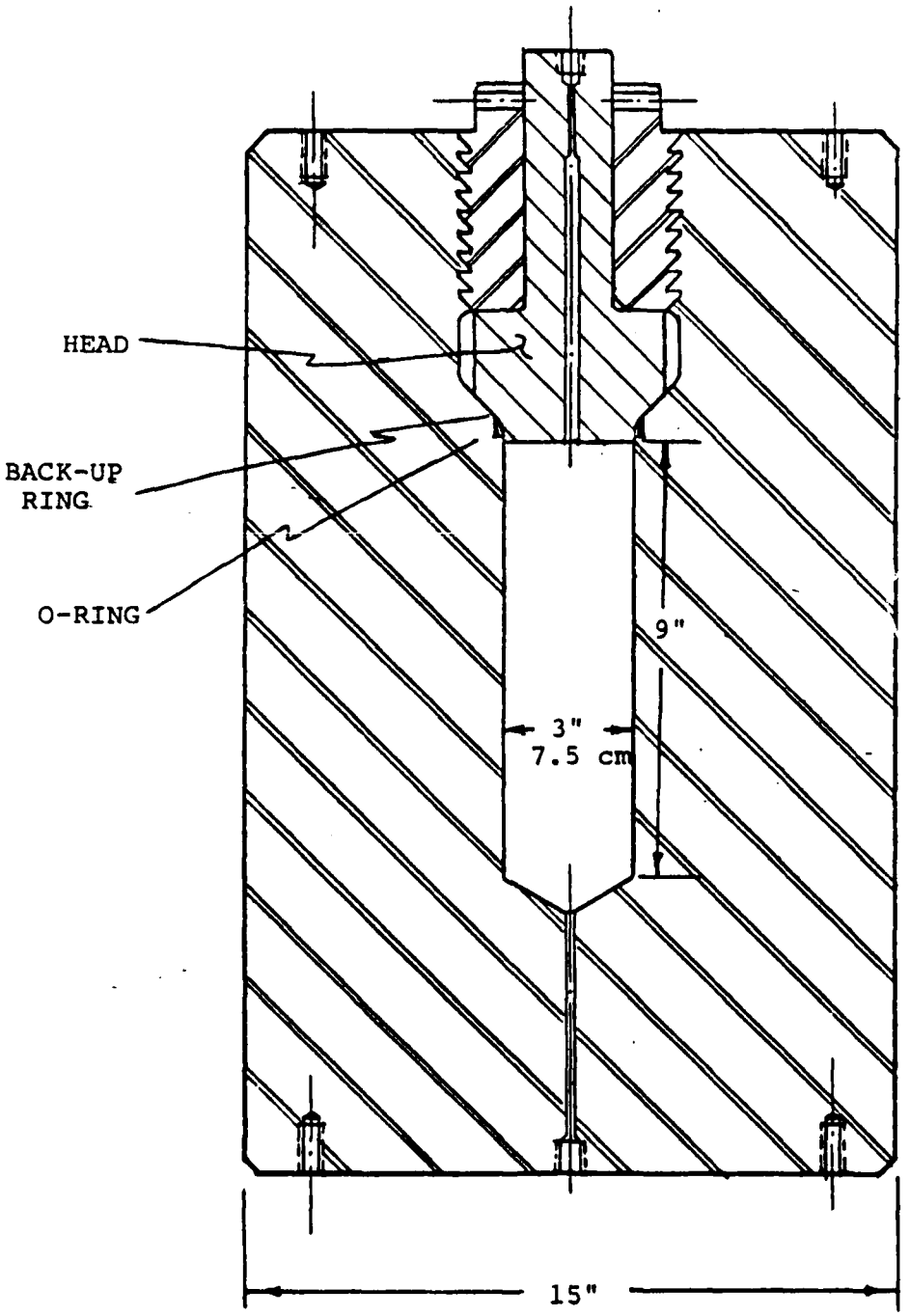
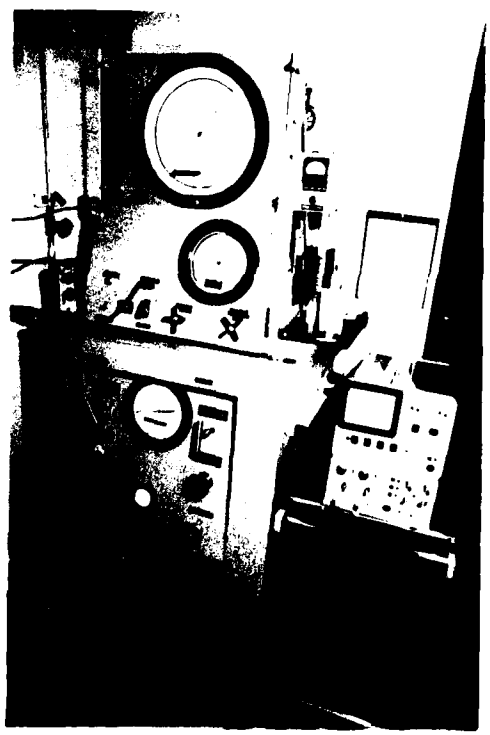
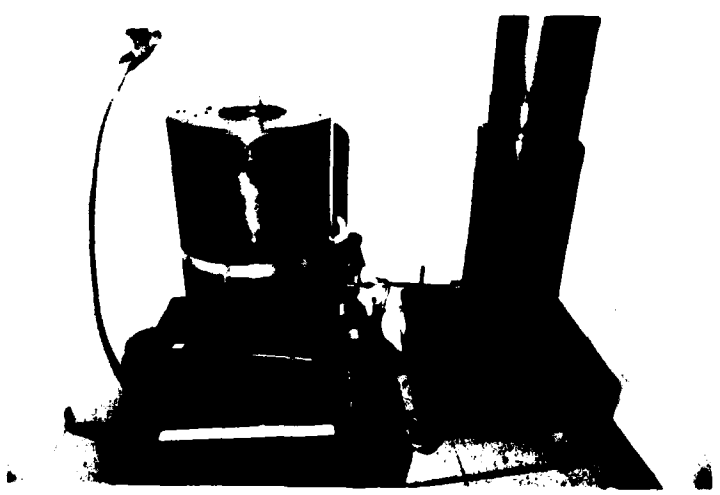


Fig. 2-3 Configuration of high pressure vessel showing overall dimensions.



Control panel of high pressure combustor



Combustor (on left), accumulator (on right) and strand holder (in foreground)

Fig. 2-4 Photographs of high pressure combustion apparatus developed at Princeton University.

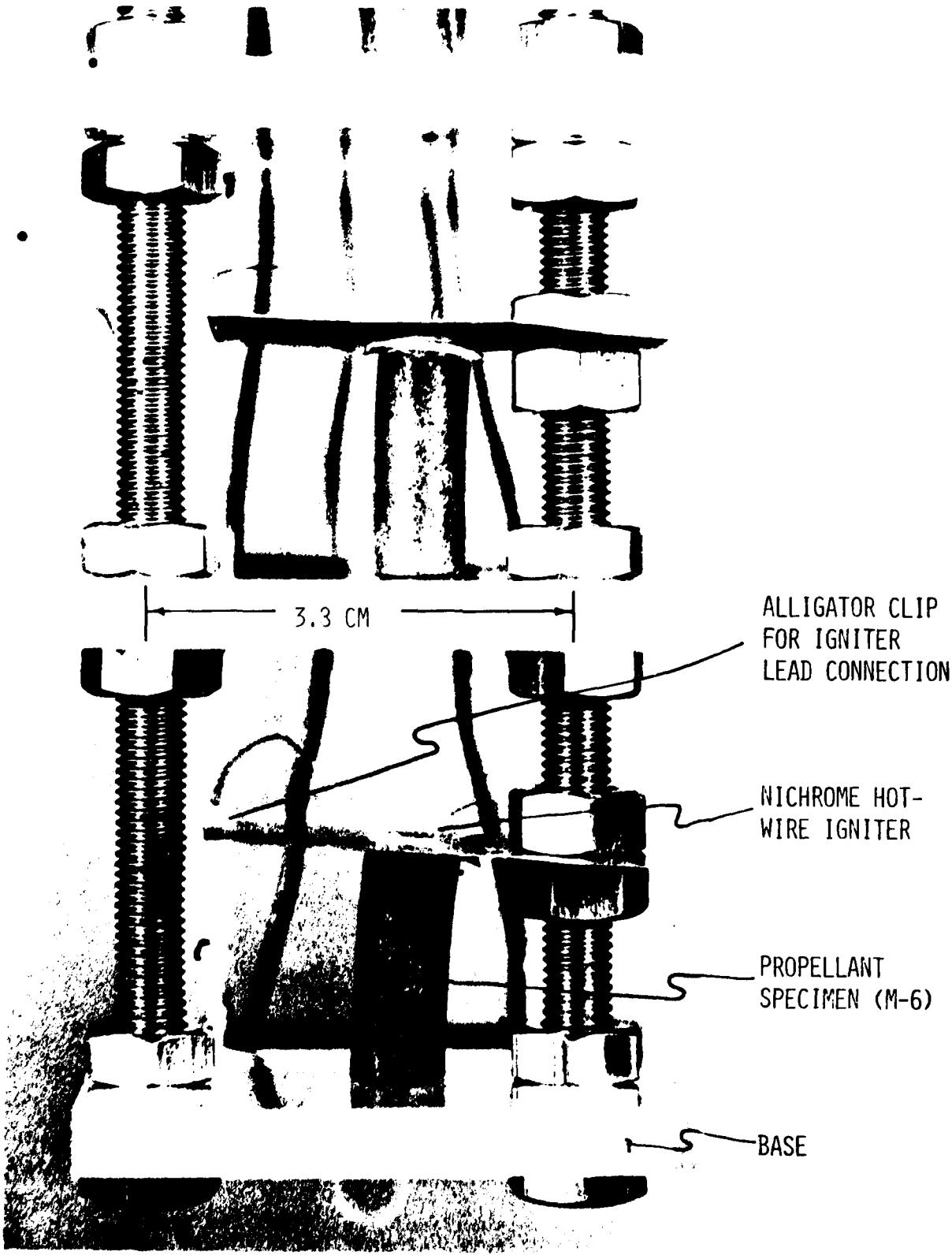


Fig. 2-5 Arrangement for holding and igniting propellant specimens.

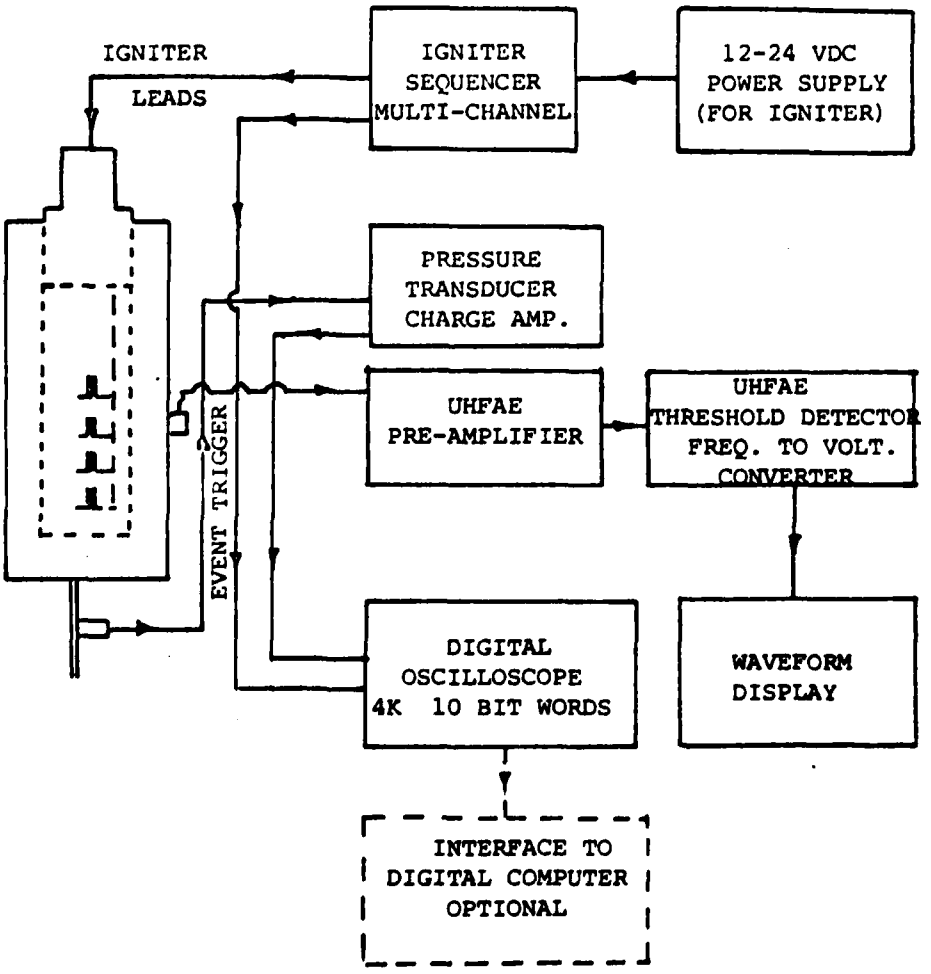


Fig. 2-6 Instrumentation used to measure burning time interval, acoustic emissions, and pressure rises.

conditioned by a frequency-to-voltage (FTV) converter which was set to produce a 1 to 10V signal when rapid changes in the acoustic emission frequency occur, i.e., the onset of combustion and propellant burnout. The output from the pressure transducer is not filtered. A typical pressure rise during a test is 2 to 4% of the mean pressure. The burn duration is determined by measuring the period of either the UHFAE signal or the pressure change. This burning rate measurement technique eliminates the drilling of holes for breakwires.

The UHFAE and pressure transients are stored in a digital oscilloscope capable of sampling the conditioned data at rates in excess of 100 kHz. The digital oscilloscope has a cursor readout of time and voltage. The output of a calibrated time-mark generator is used as a time reference to determine the accuracy of the internal timing of the digital oscilloscope. The present data recording system incorporates the Nicolet 1090A digital oscilloscope which stores 4096 data points and permits burning time intervals and uncalibrated pressure increases to be read directly from the stored digital data.

One of the accomplishments of this study was to make direct determinations of the burning rates of as-manufactured propellants, which in this case were propellant grains with seven perforations and outside diameters ranging from 0.6 to 0.8 cm and lengths ranging from 1.0 to 1.8 cm. To accomplish this, the grains were burned in the lengthwise direction. Data were obtained from single grains since testing showed that there is no apparent advantage to using multi-grain procedures.

To prepare the test specimens, an apparatus (described in Appendix A) was developed to machine the propellant specimens to a prescribed length (within ± 0.025 mm) and to insure that the top and bottom surfaces are parallel (within ± 0.025 mm). The internal perforations, the outer perimeter, and the base of the grain were inhibited. A flattened nichrome-wire igniter in zig-zag form was mounted on one end of the strand with a smear of cement. To promote uniform flame spreading across

the surface, a thin (0.025 cm) paper composition disk was held lightly against the nichrome wire, thereby forcing the flame to spread rapidly across the end of the grain.

The strand and its mount assembly were installed in the combustor which had been prefilled with tap water of controlled (± 0.3 K) temperature and the system was pressurized to the desired pressure. The modifications to achieve precise temperature control of the pressurization medium were added during the latter part of the study. Temperature control is achieved by circulating the pressurization liquid (usually tap water) through a pump-driven temperature controller. To avoid questions concerning the immersion time, ignition was programmed to occur three minutes after the propellant was first immersed.

At the present point in the technique development, an intermediate stage of experiment automation has been demonstrated. Although a single grain may be burned during each chamber pressurization to obtain about 4 tests per hour, another method permits up to four individual burning rate experiments during a single pressurization (see Section 2.2) with the data reduced automatically using a Fortran program executed on a minicomputer.

In most cases, the liquid medium effectively prevented flame spreading along the side of the propellant strands. However, in the experiments discussed in this report, the grains are inhibited (with a bituminous paint) to eliminate all questions concerning flame spreading into the perforations.

Previous studies[2,5] have demonstrated that when the experiment is properly designed, burning in a liquid medium does not affect burning rate. High-speed photographs reveal that the combustion gases issuing from the burning surface form a gaseous atmosphere (i.e., a pocket of combustion gases surrounding the flame zone) near the top of the burning strand which prevents the surrounding liquid from coming into contact with the burning surface.[6] However, if either the pressure is sufficiently low or the cross-sectional dimensions of the strand are

sufficiently small, the momentum of the gases issuing from the burning surface will be too low to effectively exclude the surrounding liquid. The high-speed photographs indicate at sufficiently low pressures the periodic enlargement and contraction of the gas pocket interferes with the propellant flame zone. In the present studies, the pressure range and propellant dimensions were well above the threshold required for good data. Conclusive evidence of this was obtained from examination of the surfaces of extinguished grains.[1]

2.2 Multiple Tests During Single Pressurization

An apparatus was developed and a methodology demonstrated for testing multiple propellant specimens during a single pressurization of the combustor. A special pressure combustor head and specimen holder assembly were fabricated which can accommodate four specimens and four independent igniter circuits. It is believed that the present configuration can accommodate as many as eight specimens. As shown in Figs. 2-5 and 2-7, the specimens are arranged vertically and are burned from top to bottom. In this manner, the hot gases from the burning propellant do not come into contact with succeeding specimens. Methods of successively igniting grains by using an upper grain to ignite the grain immediately below it were explored. While it was possible to ignite the grains in succession, the ignition and burnout events were not sufficiently well defined.

A controller was designed and fabricated to energize the sequence of separate hot-wire igniter circuits at prescribed time intervals. The ignition delay for each circuit can be set independently.

Figures 2-8 and 2-9 are copies of a graphical display of the pressure-versus-time and acoustic-emission-versus-time responses produced by burning four M26 specimens at 0.2 second intervals. The data were digitized and then transmitted to a digital computer for data reduction. The data can be analyzed in the time-sharing mode and displayed on a scope (e.g.,

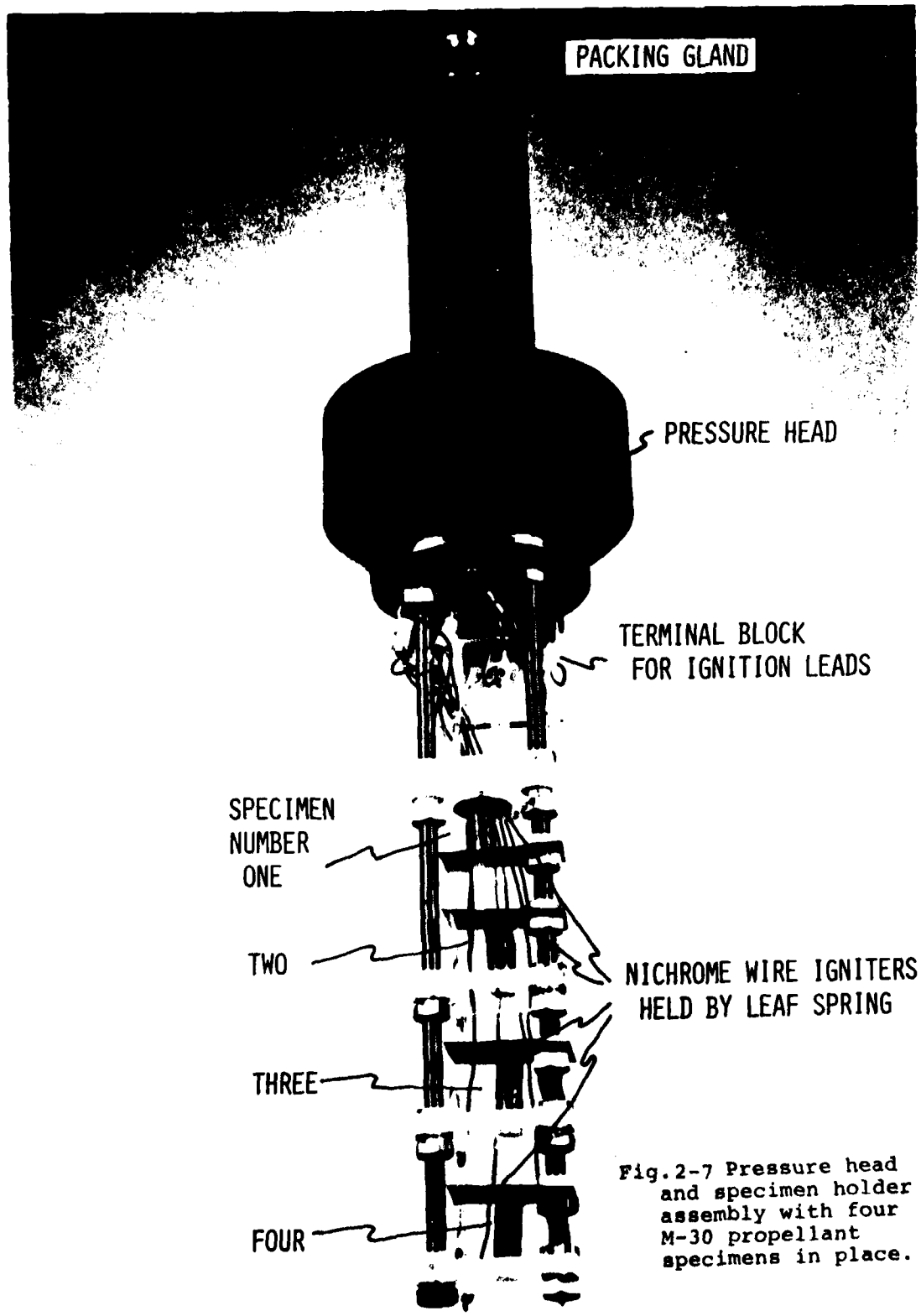


Fig. 2-7 Pressure head and specimen holder assembly with four M-30 propellant specimens in place.

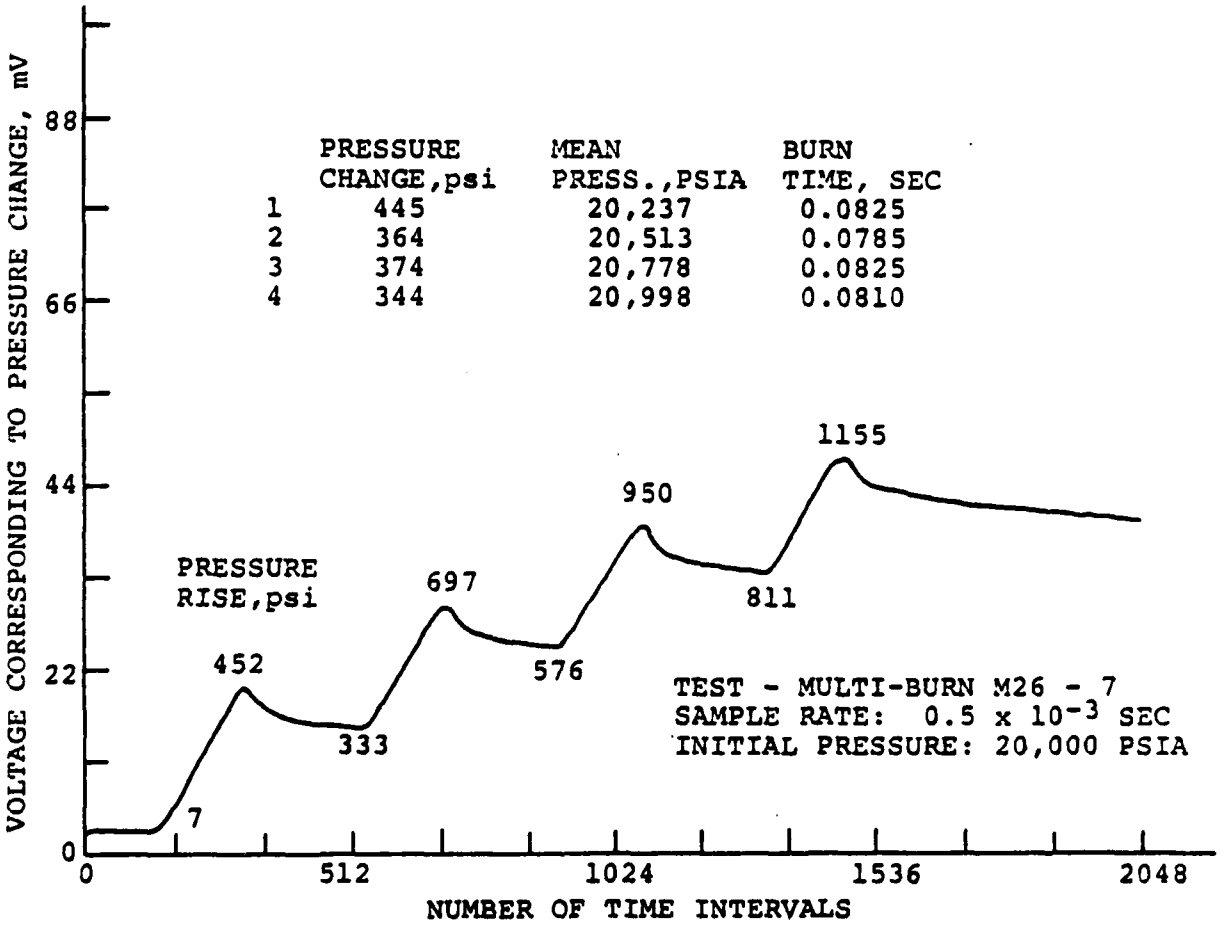


Fig. 2-8 Pressure versus time response produced by burning four M26 grains during a single pressurization.

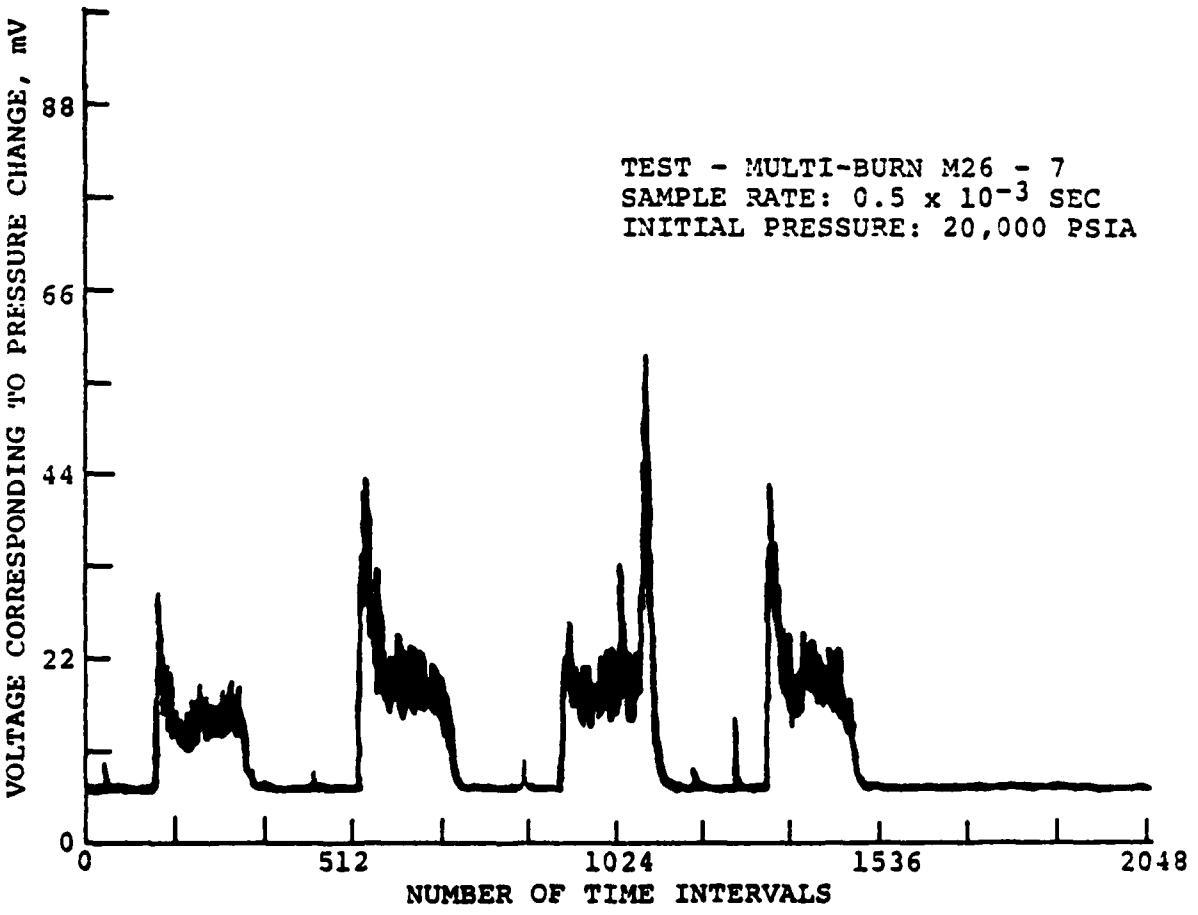


Fig. 2-9 Ultra-high acoustic emission produced by burning four M26 grains during a single pressurization.

Tektronix 4013); a hard copy of the result can be obtained (e.g., on the Tektronix 4610). Figure 2-8 shows the pressure rise produced by each burn. The pressure rises of 300 to 450 psi are approximately 1.5 to 2.3% of the total pressure. The data are reported at the mean pressure during the burn. A computer program was developed to automatically determine the burning time interval and average pressure associated with each specimen. The computer program recognizes the time at which the pressure level unambiguously departs from the initial pressure level based on the criterion that five successive points exceed the mean; the time corresponding to the first point in the series is taken as the beginning of burning. The time at which the pressure peaks is recognized as the intersection of two least squares straight lines through 10 to 25 points on each side of the peak; the time corresponding to the intersection is taken as the end of burning. Figure 2-9 shows the sharply defined acoustic emission associated with the burning of each specimen. The small "blip" that precedes the sustained signal is produced by the initial power to the igniter. The overall method functions very well and is recommended for use in subsequent experiments.

2.3 System for Use in Other Laboratories

This study demonstrated that the experimental approach developed and employed in this study is highly reliable and easy to use. Thus, it should be readily adaptable for use in other laboratories and for use in routine repetitive testing situations. It should be noted that the apparatus at Princeton University is a prototype which was intended for use by research personnel; as such it contains several features that require special attention. However, if implemented in plants or in other laboratories, it is highly recommended that a second generation system be fabricated and that the present system be retained in its present configuration mainly for research purposes. A second generation system would have fewer components, be easier to maintain, less expensive to fabricate, and require less skilled operator training.

The appendices to this report are intended to provide potential users more details on how to set up the apparatus and operate it. Appendix A describes the steps which are specific to the experiment. Since the variety of laboratory data recording instrumentation is very wide, it is assumed that potential users will adapt their own mode of instrumentation to this task. Appendix B contains the requirements for the basic high-pressure components. Appendix C describes three special purpose data acquisition and analysis approaches.

3.0 BURNING RATE MEASUREMENTS

To carry out the objectives of the study, data were obtained for several series of nitrocellulose propellants. Data for the following propellants are tabulated in this report:

Single base (Formulation given in Table 3-1):

M1 from Lot RAD-PE-441-P
" " " -Q
" " " -T
" " " -U

Double base (Formulation given in Table 3-3):

M26E1 from Standard Lot RAD-67268.
M26E1 from Current Lot RAD-69700.

Triple base (Formulation given in Table 3-7):

M30 from Standard Lot RAD-63574
M30 from Lot M30-150 (CAMBL M30 Pilot Lot).
M30 from Lot M30-151 (CAMBL M30 Pilot Lot).
M30 from Lot RAD-PE-268-1 (CAMBL M30 Pilot Lot).
M30 from Current Lot RAD-69676.

In addition, burning rate data were obtained for an HMX composite propellant with a polyurethane binder. Such propellants are in the developmental stage.

3.1 Data for AUTOCAP M1 Single Base Propellants

Burning rate data for two propellant lots from the AUTOCAP M1 series[7,8] RAD-PE-441-P and -Q were obtained as part of this study. Burning rate results for Lots RAD-PE-441-T and -U were reported in Ref. 1 and the details will not be repeated in this report. Table 3-1 summarizes the formulation variations and properties of the four lots. Table 3-2 and Fig. 3-1 summarize the burning rate data at four pressures. Note that within a given lot the specimen-to-specimen variations in burning rate are high, as indicated by the coefficient of variations, cov, (i.e., the standard deviation expressed as a percentage of the mean) values in excess of 5%.

An explanation of the M1 burning rate variability has been offered previously.[1] Three observations are consistent with the M1 burning rate tests which gave irregular burning rates: (1) intervals of abnormally high acoustic emission, (2) gradual decrease in pressurization rate at strand burnout, and (3) extinguished burning surfaces which are irregular and pitted. The burning rate variability is associated with the propellant itself, rather than the experiment, since coefficients of variations of better than 1% are readily obtainable for propellant lots which burn uniformly.

Table 3-1

AUTOCAP M1 Propellants Used in Experiments
Basic Lot M1 RAD-PE-441

Percentage by Weight Lot	P	Q	T	U
Nitrocellulose[a] (13.15% nitration)	84.74	85.02	85.29	84.73
Dinitrotoluene	9.65	9.78	9.64	9.97
Dibutylphthalate	5.61	5.20	5.07	5.30
Diphenylamine[b]	1.10	1.07	1.06	1.07
K_2SO_4 [b]	0.62	0.53	2.08	2.10
Total volatiles	0.95	2.49	1.36	2.67
Residual Solvent	0.18	0.49	0.53	0.27
Water	0.77	2.00	0.83	2.40
Grain diameter, cm	0.60	0.61	0.60	0.60
Relative Quickness	89.6	79.9	86.0	73.7
Relative Force	100.7	98.6	97.9	94.7
Formulation variation Total Volatiles	Low	High	Low	High
K_2SO_4	Low	Low	High	High

[a]Wood sulfite cellulose.

[b]Added to basic propellant.

Table 3-2

Summary of Burning Data for Autocap M1 Propellant
M1 RAD-PE-441

LOT P				
$\bar{p}$, psi	10,300	20,200	30,200	40,200
$\bar{p}$, MPa	71.0	139.3	208.2	277.2
$\bar{r}$, cm/s	5.44	10.40	13.79	17.88
Cov, %	1.3	6.7	--	--
No. Tests	4	6	3	3
LOT Q				
$\bar{p}$, psi	10,300	20,200	30,200	40,200
$\bar{p}$, MPa	71.0	139.3	208.2	277.2
$\bar{r}$, cm/s	5.31	9.45	12.33	18.26
Cov, %	3.9	5.8	2.1	5.7
No. Tests	8	2	3	3
LOT T				
$\bar{p}$, psi	10,300	20,200	30,200	40,200
$\bar{p}$, MPa	71.0	139.3	208.2	277.2
$\bar{r}$, cm/s	5.31	11.60	16.37	17.68
Cov, %	2.8	9.1	13.1	1.0
No. Tests	4	7	6	3
LOT U				
$\bar{p}$, psi	10,200	20,200	30,200	40,200
$\bar{p}$, MPa	71.0	139.3	208.2	277.2
$\bar{r}$, cm/s	4.77	9.18	13.02	17.55
Cov, %	--	2.5	--	1.9
No. Tests	2	6	2	4

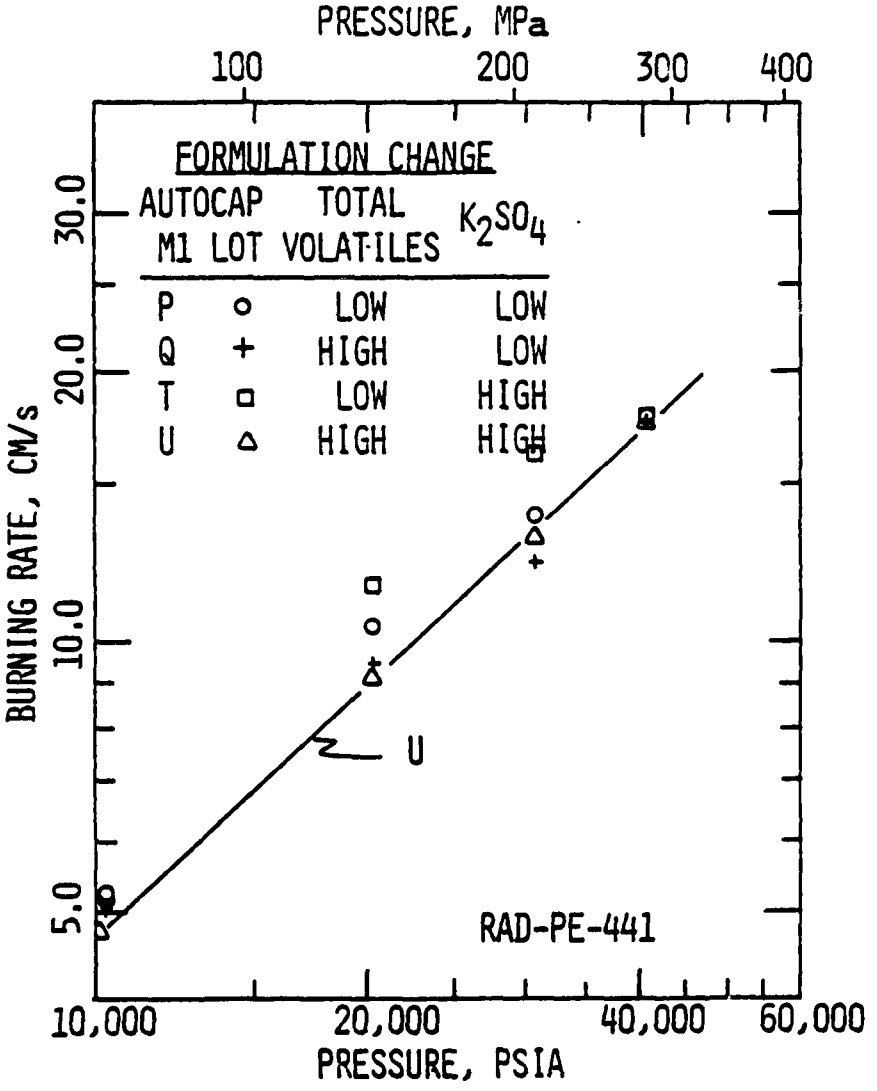


Fig. 3-1 Comparison of four lots of M1 single base propellants which were purposely formulated to have variations representing the extremes of the specification.

3.2 Data for M26E1 Double Base Propellants

Burning rate data were obtained for two lots of M26E1 double base propellants (formulation given in Table 3-3). One of the lots is the standard, RAD-67268, and the other is a current production lot, RAD-69700. The data from individual burning rate experiments for lots RAD-67268 and RAD-69700 are summarized in Tables 3-4 and 3-5. The consistency of these burning rate data is very good. Note that the cov for the burning rate is approximately 1%. The burning rate differences between the two propellants are also approximately 1%. The data points plotted on Fig. 3-2 illustrate the small differences between the two propellants (see Table 3-6 for a point-by-point comparison).

These data are a demonstration that (to a first approximation) the techniques developed as part of this study are capable of isolating burning rate differences of approximately 1%.

Table 3-3

Nominal formulation of M26E1 propellant

Nitrocellulose (13.15% nitration)	67.25
Nitroglycerin	25.00
Barium nitrate	0.75
Potassium nitrate	0.70
Ethyl centralite	6.00
Graphite	0.30
	100.00
Volatiles	
Ethyl alcohol (residual)	1.20
Water residual	0.30

Table 3-4

Tabulation of burning rate data for M-26E1 (Lot RAD-67268)
(Standard Lot)

TEST	PRESSURE INITIAL psi	PRESSURE Δp psi	BURNING RATE cm/s	QUALITY OF PEAK FOR TANGENT	STATISTICAL PARAMETERS AND SUMMARY
334	10,000	363	6.788	7	$\bar{p}$ = 10,200 psi
335	↓	379	6.702	9	_ = 71.0 MPa
336	↓	381	6.615	8	$\bar{r}$ = 6.687 cm/s
337	↓	360	6.682	9	S_r = 0.065
338	↓	380	6.650	9	Cov = 1.0%
					T_0 = 12.5 C
321	20,000	305	13.21	--	$\bar{p}$ = 20,200 psi
322	↓	310	13.24	8	_ = 139.3 MPa
323	↓	310	13.17	7	$\bar{r}$ = 13.25 cm/s
324	↓	339	13.38	9	S_r = 0.091
					Cov = 0.7%
					T_0 = 16 C
325	30,000	295	19.31	6	$\bar{p}$ = 30,200 psi
326	↓	290	19.33	6	_ = 208.2 MPa
327	↓	286	19.04	7	$\bar{r}$ = 19.00 cm/s
328	↓	286	18.93	7	S_r = 0.283
329	↓	286	18.72	8	Cov = 1.5%
330		278	18.68	8	T_0 = 15 C
331	40,000	294	24.18	8	$\bar{p}$ = 40,100 psi
332	↓	294	24.26	7	_ = 276.5 MPa
333	↓	265	24.15	7	$\bar{r}$ = 24.20 cm/s
					S_r = 0.061
					Cov = 0.3%
					T_0 = 12 C

$r = 0.001131\ p^{0.942}$ cm/s; p in psi; $r^2_{gof} = 0.9986$

Multi-perforated grains burned as endburners.

Table 3-5

Tabulation of burning rate data for M-26E1 (Lot RAD-69700)
(Production Lot)

TEST	PRESSURE INITIAL psi	Δp psi	BURNING RATE cm/s	QUALITY OF PEAK FOR TANGENT	STATISTICAL PARAMETERS AND SUMMARY
317	10,000	274	6.659	10	$\bar{p}$ = 10,100 psi
318	↓	300	6.717	9	= 69.6 MPa
319		264	6.637	10	$\bar{r}$ = 6.685 cm/s
320		258	6.727	10	S_r = 0.044
					Cov = 0.7%
301	20,000	316	13.05	9	$\bar{p}$ = 20,200 psi
302	↓	310	13.00	9	= 139.3 MPa
303		295	13.08	8	$\bar{r}$ = 13.09 cm/s
304		293	13.15	9	S_r = 0.069
305		294	13.16	9	Cov = 0.5%
306	30,000	282	19.25	10	$\bar{p}$ = 30,100 psi
307	↓	273	18.83	10	= 207.5 MPa
308		285	19.31	10	$\bar{r}$ = 19.09 cm/s
309		274	19.05	9	S_r = 0.197
310		279	18.89	10	Cov = 1.0%
311		289	19.20	7	
312	40,000	306	28.86	Out 7	$\bar{p}$ = 40,200 psi
313	↓	287	24.77	10	= 277.2 MPa
314		300	24.89	9	$\bar{r}$ = 24.57
315		275	24.34	8	S_r = 0.303
316		288	24.28	8	Cov = 1.2%

$r = 0.001093p^{0.946}$ cm/s; p in psi; $r^2_{gof} = 0.9996$

Ambient temperature 15 C.
Multi-perforated grains burned as endburners.

Table 3-6

Comparison of burning rate data from M26E1 Lots
RAD-67268 (Standard)
RAD-69700

LOT RAD-	PRESSURE psi	BURNING RATE cm/s	PRESSURE psi	BURNING RATE cm/s	PRESSURE psi	BURNING RATE cm/s	PRESSURE psi	BURNING RATE cm/s	BURNING RATE EXPONENT
67268 (standard)	10,200	6.687	20,200	13.25	30,200	19.00	40,100	24.20	0.942
69700	10,100	6.685	22,200	13.09	30,100	19.09	40,200	24.57	0.946
Difference %		-0.03		-1.2		+0.5		+1.5	

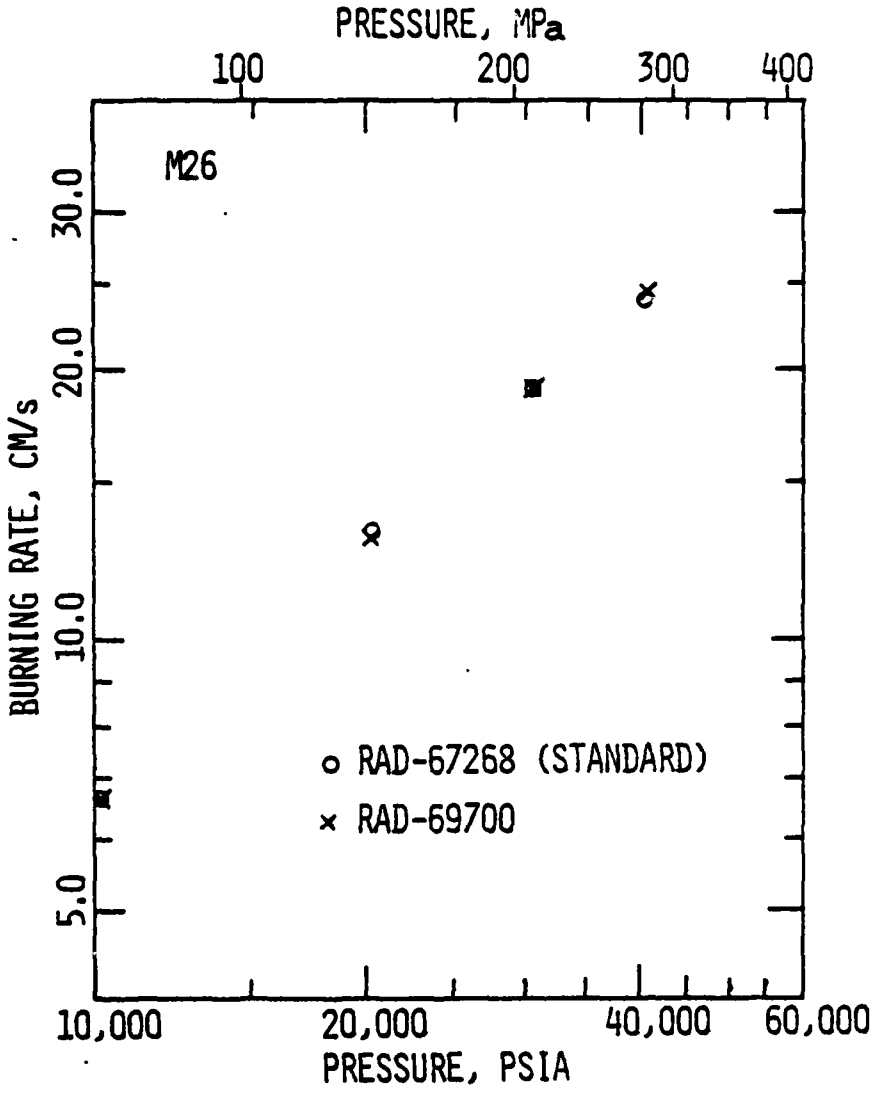


Fig. 3-2 Burning rate comparison of two lots of M26 double base propellant.

3.3 Data for M30 Triple Base Propellants

Burning rate data for five M30 lots are presented in Figs. 3-3 and 3-4. The burning rate trends are accurately correlated on ln r vs ln p plots; however, as indicated in Tables 3-8 through 3-11, the variability of the individual tests are about three times higher than for M26. The burning rate variability may be caused by nonuniform dispersion of the nitroguanidine.

Burning rate data, obtained over three decades of pressure, are plotted in Fig. 3-5 and tabulated in Tables 3-12 through 3-14. This was done in support of one of the Army Laboratories which is considering ignition, flame spreading, and pressurization of beds of M30 grains. Thus, burning rates were required at low pressure. The burning rate data below 8 MPa (1200 psi) were obtained using N_2 as the pressurizing medium; all other aspects of the experiment remained unchanged.

Table 3-7

Formulations of M30 propellants

	SPECIFICATION	RAD-PE -268-1	RAD-268 -1-150	RAD-268 -1-151
Nitrocellulose (13.15% nitration)	28.0 ± 1.3	28.36	29.50	27.89
Nitroglycerin	22.5 ± 1.0	22.15	21.72	22.41
Nitro Guanidine	47.7 ± 1.0	47.65	46.93	47.81
Barium nitrate	--			
Potassium nitrate	--			
Ethyl centralite	1.5 ± 0.10	1.52	1.51	1.52
Graphite	0.20 max	0.13	0.08	0.10
Cryolite	0.30 ± 0.10	0.32	0.34	0.37
Volatiles				
Ethyl alcohol (residual)				
Water residual				
Total volatiles	0.50 max	0.23	0.14	0.30
RQ* at 33 C		99.77	102.95	97.67
RF* at 33 C		99.25	99.63	99.54
Heat of Explosion, cal/g		978.0	977.0	976.3

*Compared to RAD-PE-63574

Table 3-8

Tabulation of burning rate data for M30 (Lot RAD-63574)
(Standard Lot)

TEST	P_{mean} psig	r cm/s	T_0, C	QUAL. OF PEAK/ DECISION	STATISTICAL PARAMETERS AND SUMMARY
1	10,720	6.513	23.8	10	$\bar{p}$ = 10,730 psi
2	10,750	7.451	23.8	8 out	= 73.98 MPa
3	10,750	6.626	24.0		$\bar{r}$ = 6.498 cm/s
4	10,710	6.354	24.2	7	S_r = 0.137
5	10,750	8.467	24.8	5 out	Cov = 2.1%
6	20,670	11.75	24.5	9	$\bar{p}$ = 20,650 psi
7	20,660	11.95	24.7	9	= 142.4 MPa
8	20,660	13.53	24.8	9 out	$\bar{r}$ = 11.70 cm/s
14	20,630	14.17	22.5	7 out	S_r = 0.400
15	20,630	11.12	22.5	10	Cov = 3.4%
37	20,620	14.37	23.3	8 out	
38	20,650	11.99	33.6	8	
9	30,650	18.51	24.9	9	$\bar{p}$ = 30,660 psi
10	30,670	16.41	24.9	10	= 211.4 MPa
11	30,670	17.44	24.9	10	$\bar{r}$ = 17.51 cm/s
16	30,650	15.77	22.3	10 out	S_r = 0.779
17	30,660	17.29	22.5	10	Cov = 4.4%
39	30,670	17.91	23.7	9	
12	40,660	22.33	25.0	10	$\bar{p}$ = 40,650 psi
13	40,660	22.61	25.2	9	= 280.3 MPa
40	40,630	21.97	23.4	10	$\bar{r}$ = 22.30 cm/s
					S_r = 0.319
					Cov = 1.4%

$r = 0.00112\ p^{0.933}$ cm/s, p in psi; $r^2_{gof} = 0.9993$

Table 3-9

Tabulation of burning rate data for M30 (Lot RAD-TE-268-1-150)
(CAMBL Pilot Lot)

TEST	P_{mean} psig	r cm/s	T_0, C	QUAL. OF PEAK/ DECISION	STATISTICAL PARAMETERS AND SUMMARY
30	10,690	7.981	22.5	8 out	$\bar{p}$ = 10,700 psi
31	10,720	6.780	22.3	9	= 74.74 MPa
32	10,700	6.937	22.3	8	$\bar{r}$ = 6.80 cm/s
33	10,680	6.689	22.5	10	S_r = 0.125
					Cov = 1.8%
34	30,600	18.27	22.5	10	$\bar{p}$ = 30,580 psi
35	30,600	18.80	22.7	10	= 210.8 MPa
36	30,550	19.00	22.8	10	$\bar{r}$ = 18.69 cm/s
					S_r = 0.377
					Cov = 0.020

Table 3-10

Tabulation of burning rate data for M30 (Lot RAD-TE-268-1-151) (CAMBL Pilot Lot)

TEST	P_{mean} psig	r cm/s	T_0, C	QUAL. OF PEAK/ DECISION	STATISTICAL PARAMETERS AND SUMMARY
26	10,730	6.783	21.8	8	$\bar{p}$ = 10,690 psi
27	10,700	6.505	21.7	9	_ = 73.71 MPa
28	10,730	7.502	22.2	8 out	$\bar{r}$ = 6.658 cm/s
29	10,730	6.844	22.2	9	S_r = 0.144
52	10,660	6.677	19.7	8	Cov = 2.2%
53	10,670	6.487	19.7	8	
54	10,660	6.654	19.8	8	
41	30,590	16.69	23.8	10	$\bar{p}$ = 30,600 psi
42	30,600	17.32	24.0	10	_ = 210.9 MPa
43	30,620	16.52	24.2	10	$\bar{r}$ = 16.56 cm/s
55	30,600	16.61	19.8	9	S_r = 0.504
56	30,610	16.51	19.8	10	Cov = 3.0%
57	30,590	15.74	19.8	8	

Tests 26-29 & 41-43 are referred to as first set.
Tests 52-57 are referred to as second set.

Table 3-11

Tabulation of burning rate data for M30 (Lot RAD-268-1)
(CAMBL Pilot Lot)

TEST	P_{mean} PSIG	r cm/s	T_0, C	r_{25} cm/s	QUAL. OF PEAK/ DECISION	STATISTICAL PARAMETERS AND SUMMARY
367	11090	8.499	24	8.541	10 A R*	$\bar{p}$ = 10670 psi
368	10640	6.528	24	6.561	7 R	= 73.57 MPa
369	10670	6.324	24	6.356	8 A	$\bar{r}_{25}$ = 6.410 cm/s
370	10710	6.309	25	6.309	9 A	S_r = 0.109
371	10670	6.413	25	6.413	9	Cov = 1.7 %
372	20570	11.65	25	11.65	8 A	$\bar{p}$ = 20560
373	20580	10.84	↓	10.84	8	= 141.8
374	20520	11.40	↓	11.40	6	$\bar{r}_{25}$ = 11.45
375	20540	11.38	↓	11.38	5 A	S_r = 0.415
376	20570	11.97	↓	11.97	9	Cov = 3.6%
377	30530	16.30	25	16.30	9 A	$\bar{p}$ = 30550
378	30560	16.28	↓	16.28	9 A	= 210.6
379	30520	17.14	↓	17.14	8 R	$\bar{r}_{25}$ = 16.49
380	30580	16.24	↓	16.24	7 A	S_r = 0.434
						Cov = 2.6%
381	40570	20.27	25	20.27	7	$\bar{p}$ = 40560
382	40530	21.52	↓	21.52	6 R	= 279.7
383	40540	20.84	↓	20.84	9	$\bar{r}_{25}$ = 20.77
384	40580	20.45	↓	20.45	6	S_r = 0.554
						Cov = 2.7%

$r = 0.00174p^{0.886}$ cm/s; p in psi; $r^2_{gof} = 0.9497$

*Experiment not considered in statistical correlation.

Table 3-12

Tabulation of burning rate data for M30
(Lot RAD-69676) (Production Lot)
- Special situation of burning
in N_2 at low pressure -

TEST	p_{mean} psig	r cm/s	T_0 C	SUMMARY PARAMETERS
N15	241	0.353	22	$\bar{p}$ = 240 psi
N16	239	0.339	22	= 1.65 MPa
				$\bar{r}$ = 0.346 cm/s
N12	461	0.562	22	$\bar{p}$ = 461 psi
N13	458	0.541	22	= 3.18 MPa
N14	464	0.554	22	$\bar{r}$ = 0.552 cm/s
N9	668	0.72	22	$\bar{p}$ = 669 psi
N10	670	0.794	22	= 4.61 MPa
N11	670	0.749	22	$\bar{r}$ = 0.754 cm/s
N5	954	0.934	22	$\bar{p}$ = 954 psi
N6	950	0.965	22	= 6.58 MPa
N7	949	0.918	22	$\bar{r}$ = 0.932 cm/s
N8	962	0.911	22	
N1	1155	1.104	22	$\bar{p}$ = 1164 psi
N2	1165	1.112	22	= 8.02 MPa
N3	1165	1.142	22	$\bar{r}$ = 1.122 cm/s
N4	1170	1.120	22	

Table 3-13

Tabulation of burning rate data for M30 (Lot RAD-69676)
(Production Lot)

TEST	P_{mean} PSIG	r cm/s	T_0, C	r_{25} cm/s	QUAL. OF PEAK/ DECISION	STATISTICAL PARAMETERS AND SUMMARY
363	3510	2.731	20	2.794	7	$\bar{p}$ = 3470 psi
364	3410	2.896	↓	2.963	9	= 23.93 MPa
365	3440	2.752	↓	2.815	7	$\bar{r}_{25}$ = 2.854 cm/s
366	3500	2.778	↓	2.842	9	S_r = 0.076
		$\bar{r}$ = 2.790				Cov = 2.6%
358	5790	4.080	18	4.211	9	$\bar{p}$ = 5780 psi
359	5760	4.426	↓	4.568	8	= 39.85 MPa
360	5760	4.416	↓	4.557	7	$\bar{r}_{25}$ = 4.435 cm/s
361	5830	4.348	20	4.448	9	$\bar{S}_r$ = 0.146
362	5780	4.290	20	4.389	6	Cov = 3.3%
		$\bar{r}$ = 4.312				
352	10580	6.885	18.5	7.092	8	$\bar{p}$ = 10,560 psi
353	10560	6.630	↓	6.829	8	= 72.81 MPa
354	10530	6.321	↓	6.511	5	$\bar{r}_{25}$ = 6.967 cm/s
355	10570	6.902	↓	7.109	7	$\bar{S}_r$ = 0.254
356	10570	6.867	↓	7.073	10	Cov = 3.6%
357		6.979	↓	7.188	7	
		$\bar{r}$ = 6.764				
339	20480	12.63	21	12.86	9	$\bar{p}$ = 20,500 psi
340	20500	13.05	↓	13.28	7	= 141.3 MPa
341	20510	13.48	↓	13.72	8	$\bar{r}_{25}$ = 13.05 cm/s
342	20500	12.51	↓	12.74	8	$\bar{S}_r$ = 0.38
343	20490	12.55	↓	12.78	5	Cov = 2.9%
344	20500	12.70	↓	12.93	7	
		$\bar{r}$ = 12.82				
345	30500	17.72	21	18.04	9	$\bar{p}$ = 30,490 psi
346	30490	17.67	21	17.99	8	= 210.2 MPa
347	30470	17.38	19	17.85	9	$\bar{r}_{25}$ = 17.96 cm/s
		$\bar{r}$ = 17.54				$\bar{S}_r$ = 0.10
						Cov = 0.5%
348	40480	21.79	19	22.38	8	$\bar{p}$ = 40,490 psi
349	40490	23.58	↓	24.22	NP/out	= 279.2 MPa
350	40500	22.14	↓	22.74	8	$\bar{r}_{25}$ = 22.60 cm/s
351	40490	22.08	↓	22.68	9	$\bar{S}_r$ = 0.19
		$\bar{r}$ = 22.39				Cov = 0.9%

For p = 3,000 to 40,000 psi and T_0 = 18 to 21 C

$r = 0.00267\ p^{0.852}$ cm/s; p in psi; $r^2_{gof} = 0.9990$

Table 3-14
Summary of burning rate data
for M30 Lot RAD-69676
over three decades of pressure
Temperature 18 to 22 C

$\bar{p}$ psi	r cm/sec	C.O.V. %	Number of Tests
240	0.346		2*
461	0.552	1.9	3*
669	0.754	4.9	3*
954	0.932	2.6	4*
1,164	1.122	1.4	4*
3,470	2.790	2.6	4
5,780	4.312	3.3	5
10,560	6.764	3.6	6
20,500	12.82	2.9	6
30,490	17.59	0.5	3
40,490	22.39	0.9	4

From 240 to 1163 psi: $r = 0.00601\ p^{0.739}$ cm/s; $r^2_{gof} = 0.9983$ where p is in psi.

From 3,000 to 40,000 psi: $r = 0.00267\ p^{0.852}$ cm/s; $r_{gof} = 0.9990$ over entire pressure range

As-received grains inhibited and burned as end burners. Typical length was 0.56 inches and was known to within ± 0.001 inches.
*Burned in N_2.

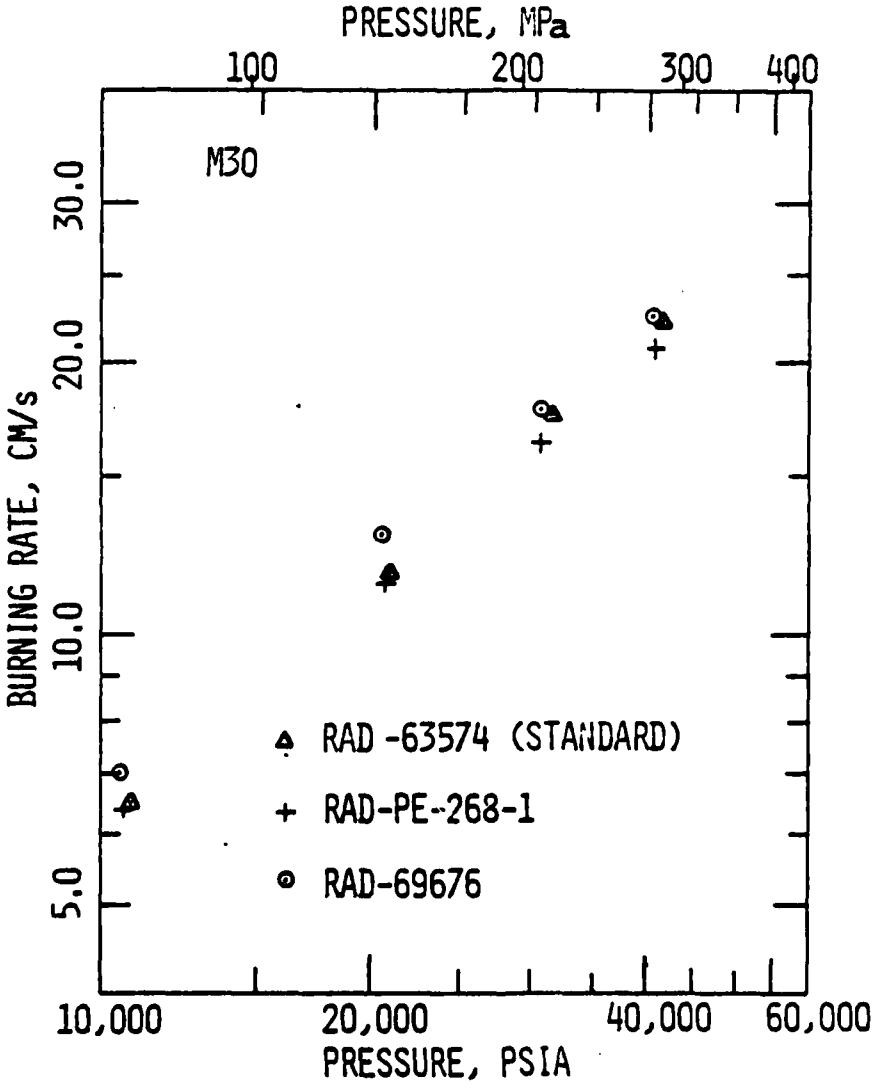


Fig. 3-3 Comparison of three lots of M30 triple base propellant.

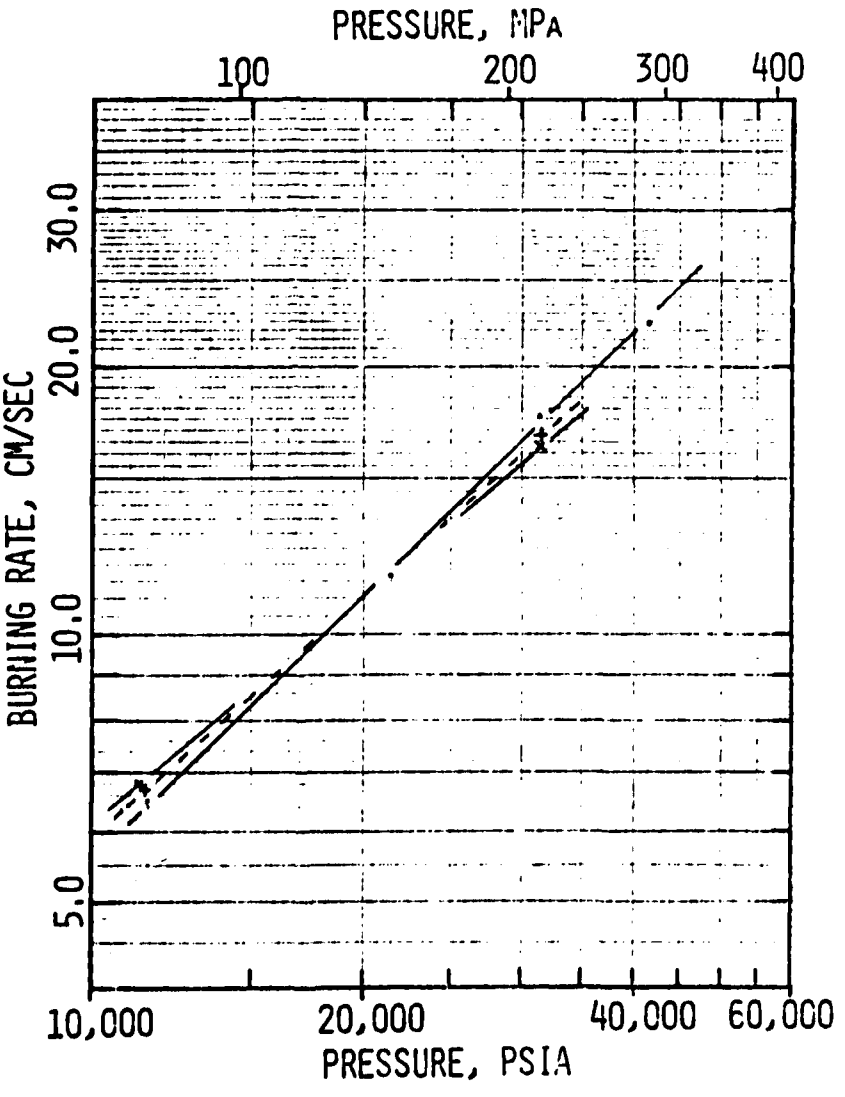


Fig. 3-4 Summary of burning rates of several M30 lots (triple base).

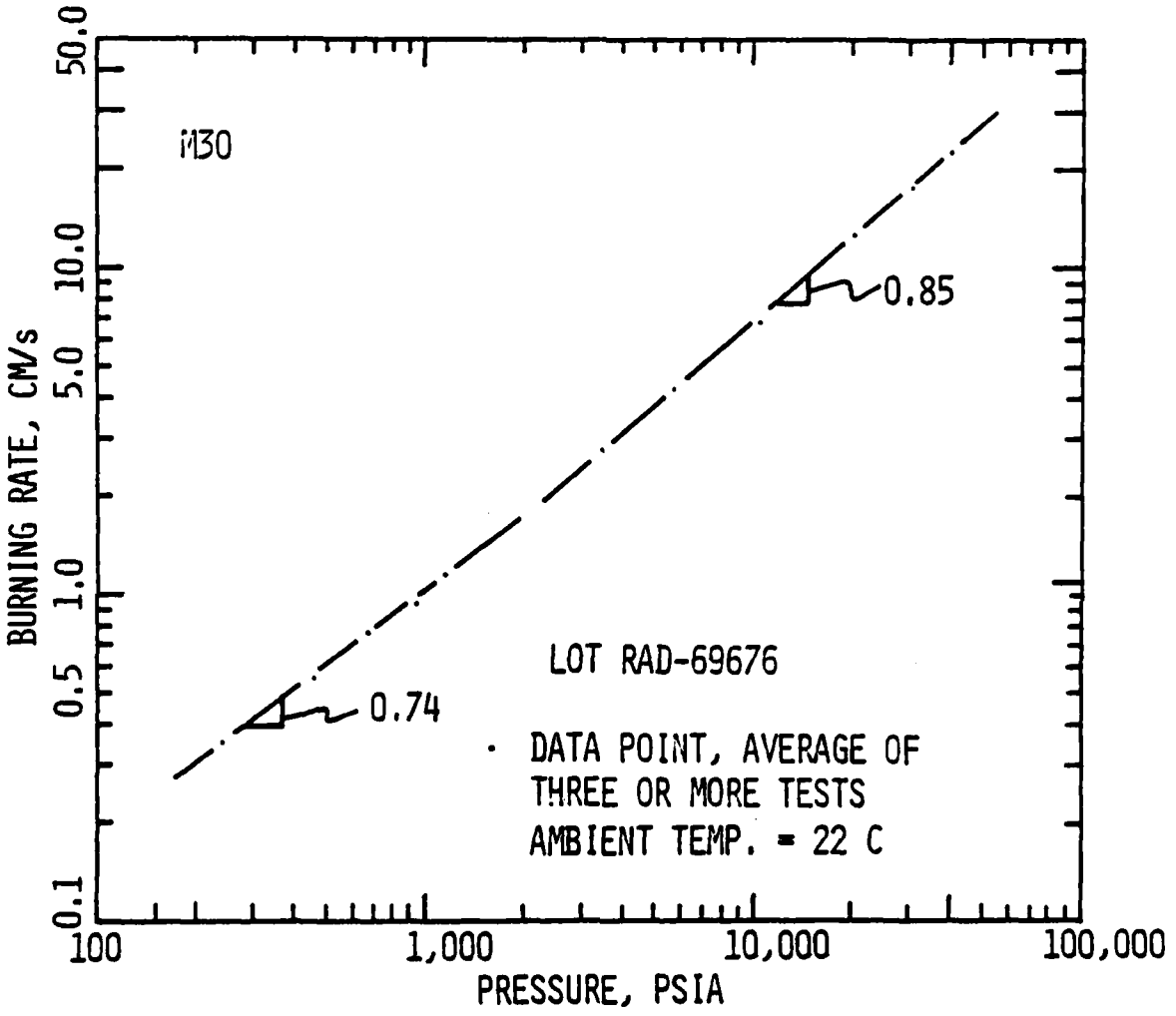


Fig. 3-5 Burning rate data for an M30 triple base propellant over three decades of pressure.

3.4 Data for HMX/Polyurethane Propellant

Burning rate measurements were made for a low flame temperature HMX/polyurethane propellant. The propellant, containing 82% HMX and 18% polyurethane, was in the form of 1.2 cm diameter wafers about 2 mm thick. The flat sides of the wafers were inhibited; the disks were cut to have two parallel surfaces about 0.8 cm apart. It is believed that thinness of the specimens may have resulted in the test-to-test variation indicated by the error bars on Fig. 3-6. The shift in burning rate exponent between 10,000 and 20,000 psi is representative of this type of propellant.

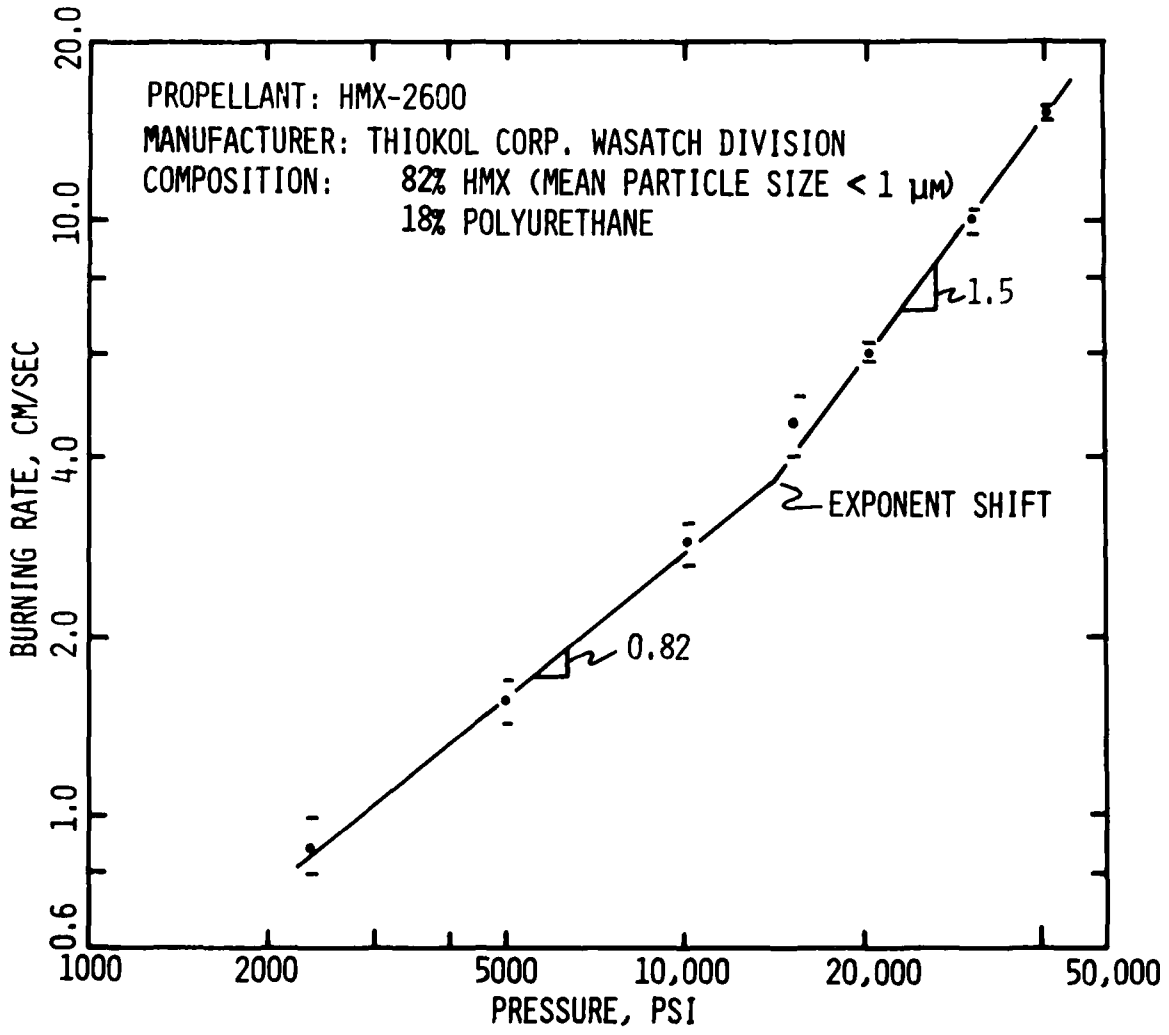


Fig. 3-6 Burning rate of HMX composite propellant showing exponent shift at approximately 18,000 psi.

4.0 BURNING RATE MEASUREMENTS FOR INTERRUPTED-PROCESS PROPELLANTS

As part of this study, experiments were performed to determine whether interrupted-process propellants can be used to obtain meaningful burning rate comparisons. These particular propellants were removed from the production line before they were fully dried; solvent-rich propellants are referred to as green propellants.

If accurate burning rates can be obtained from solvent-rich propellants, then the time interval required to detect irregularities in the production process can be reduced. It is reasonable to expect that many deviations in the manufacturing process which produce significant variations in the burning rate of finished propellants should produce corresponding variations in the burning rate of green propellants.

In anticipation of receiving the green propellant specimens from Radford Arsenal, the experimental techniques were worked out using propellant specimens which had solvents re-introduced. This was accomplished by placing known amounts of solvent (50% acetone and 50% ethyl alcohol) and a dried M26 propellant grain in a small glass vial with a vapor barrier seal. The propellant grain was placed on a wire support to prevent it from coming into direct contact with the liquid solvent. The liquid solvent was evaporated and absorbed in about one day; three additional days were allowed for the solvent to diffuse into the propellant. The weight of solvent absorbed was determined by measuring the weight gained by the propellant grain. This method produced specimens which contained about 25% solvent. At that level the burning rates were reduced by more than 40%. Also, the method of re-introducing the solvent may have caused some of the NG to leave the propellant and collect on the walls of the glass vials.

The personnel at Radford Arsenal provided Princeton University with green propellant specimens which were taken directly from the production line for Lot M30 PEI-486, placed in small glass bottles with aluminum vapor seals, and shipped directly to Princeton University. Since the objective was to test the propellant without disturbing the solvent percentage, an

accelerated process of specimen preparation (including inhibiting) and testing was worked out. All of the standard procedures were retained by completing the test procedures for groups of five specimens within two hours from opening the specimen bottle to burning the specimen. Each group of five specimens were prepared following the same time sequence.

The results summarized on Table 4-1 show that fairly consistent burning rate data were obtained. As expected, the burning rates of the solvent-rich propellants are significantly lower than those of the normally processed propellants. The cov's of the solvent-rich propellants are somewhat better than those reported in Section 3.3; this may be a result of the extra attention given to the test series.

Table 4-1

Tabulation of burning rate data for undried M30
(Green Lot PEI-486)

TEST	p_{mean} PSIG	r cm/s	T_0, C	QUAL. OF PEAK DECISION	STATISTICAL PARAMETERS AND SUMMERY
A	20,400	10.36	25	9	$\bar{p}$ = 20,410 psi
B	20,400	10.58	↓	8	= 140.7 MPa
C	20,420	11.19	↓	8 A *	$\bar{r}$ = 10.41 cm/s
D	20,400	10.24	↓	9	S_r = 0.13 cm/s
E	20,420	10.42	↓	9	Cov = 1.2%
F	20,400	10.47	↓	9	
G	40,390	17.44	25	9	$\bar{p}$ = 49,395 psi
H	40,430	18.14	↓	9	= 278.5 MPa
I	40,390	18.10	↓	6	$\bar{r}$ = 17.88
J	40,370	17.78	↓	8	S_r = 0.30 cm/s
K	40,390	18.03	↓	8	Cov = 1.7%
L	40,390	19.02	↓	8 A *	
M	40,400	17.52	↓	9 A	
N	40,400	18.13	↓	9	
O	30,400	16.36	25	9	$\bar{p}$ = 30,395 psi
P	30,390	16.92	25	9	= 209.6 MPa
					$\bar{r}$ = 16.66

*Experiment not included in statistical correlation.

5.0 BURNING RATE PRESSURE SENSITIVITY

In the process of this study, it was noted that the pressure sensitivities of individual grain burning rates, $\partial \ln r / \partial \ln p$, (referred to as the burning rate exponent) are typically 20% higher than many of the values deduced from closed chamber pressure vs time data. Table 5-1[9] compares recent data from three sources. The strand and single grain data have similar pressure sensitivities of burning rate, whereas the values deduced from closed chamber tests are appreciably lower. The higher values of burning rate exponent are generally more effective in correlating the performance of large caliber guns.[10] The techniques of deducing burning rates from closed chamber firings are presently under review by a JANNAF Committee. Possibly these large differences in pressure sensitivity will be eliminated when the closed chamber data reduction procedures are improved. Several groups are focusing attention on the errors associated with factors such as heat loss corrections, real gas effects, and uniform ignition.

The results of strand and closed chamber data obtained at the U.S. Army's Ballistic Research Laboratories between 1953-1956 were summarized recently in Ref. 11. A range of nitrocellulose-base propellants were considered including M1 and propellants with compositions similar to M26. In that report, the agreement between the burning rate exponents obtained by the two methods was often within a few percent. The greatest deviations are on the order of ± 5%. It is interesting to note that these data obtained over 20 years ago have average pressure sensitivities (for the $a + bp^n$ relationship) of between 0.93 and 1.1 and individual data series were no lower than 0.84. Thus, the good agreement between strand data and closed chamber data is obtained for pressure sensitivities comparable to those measured during this study.

Table 5-1

Comparison of burning rate pressure sensitivity measured under steady state and and closed chamber conditions

	Princeton	Feltman Lab.[9]	
	Single Grain	Strand	Closed Chamber
M1	0.943*	0.90	0.67
Lot	RAD-PE-441-U		
M26	0.946**	0.90	0.80
Lot	RAD-69700		
M30	0.886***	0.96	0.65
Lot	RAD-268-1		

*Coefficient of Determination = 0.9993
**Coefficient of Determination = 0.9996
***Coefficient of Determination = 0.9997

6.0 CONCLUSIONS

The experimental techniques and data analysis procedures for measuring burning rates of as-manufactured grains have been demonstrated using several types of nitrocellulose-base propellants. The techniques described in this report and in Ref. 1 are relatively easy to implement and are applicable to many classes of propellants.

The conclusions and observations from the data presented in this report include:

1. Burning rate measurements accurate to within a 1% coefficient of variation are achievable.
2. Burning rate variations in excess of the measurement accuracy may be attributable to propellant inconsistencies and defects.
3. As-manufactured, multi-perforated grains can be burned individually and used to obtain accurate burning rate data.
4. Burning rate consistency of M26 double-base propellant is very good, i.e., cov $\simeq$ 1%. The burning rate variability of propellants which are heterogeneous (e.g., M30 which contains NGu) or contain incompletely dispersed ingredients (e.g., M1 whose burning is affected by NC concentration) can be isolated as part of the data reduction procedure.
5. Burning rate pressure sensitivities measured from single grain experiments are consistently in the range of 0.9, about 20% higher than those deduced from recent closed chamber experiments.

The detection of acoustic emissions from burning propellants in addition to being used to time burning intervals also provides information relatable to the quality of burning, and, thus, the quality of the propellant. Excessive variation in the acoustic emission level or dominant frequencies can be the basis for identifying a propellant lot that was improperly manufactured. In the previous study,[1] acoustic emission variations and, thus,

burning rate irregularities of nitrocellulose propellants (i.e., M1 and M6) are related to the degree to which the fibrous nitrocellulose was dispersed. Nitrocellulose propellants with plasticizers (e.g., M26) which increase burning rate and improve mixing of ingredients tend to burn uniformly and have relatively small variations in their acoustic emissions. It is anticipated that examination of the acoustic emission level will be useful in diagnosing other types of propellant problems, e.g., damage to propellants produced by high strains, formulation and processing difficulties which produce dewetting of solid ingredients, and networks of small cracks or regions of porosity.

Burning rate measurements of as-manufactured, multiperforated grains coupled with analytical methods of applying the measurements can be used as part of in-process control procedures which involve single grains taken directly from intermediate phases of production processes (i.e., interrupted-process propellants). Also, this type of accurate burning rate measurement can be used in a wide variety of applications, e.g., (1) the development and application of ballistic performance models, (2) analyses to determine the significance of grain-to-grain variations on the variability of bulk charges consisting of hundreds of grains, and (3) interpretations of burning rates deduced from closed chambers in terms of steady state burning rates.

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APPENDIX A

PROCEDURES FOR SETTING-UP AND CONDUCTING EXPERIMENTS USING HIGH PRESSURE COMBUSTOR APPARATUS

This appendix lists (and where necessary describes) the steps which are routinely used to obtain the data presented in this report. Figure A-1 is a schematic representation of the hydraulic hardware. Figure A-2 shows the console to control the hydraulic system and is representative of the prototype system. Figure 2-6 in Section 2.0 of this report is an instrumentation diagram. The material in this section supplements the broader descriptions given in Section 2 of the main text. Attention is focused on the systematic testing that uses only the essential elements of the apparatus. Accordingly, the description that follows bases the burning time interval on the period of pressure rise, since the pressure measurement is required to determine the mean pressure. The acoustic emission is measured to diagnose burning rate irregularities.

I. INSTRUMENTATION SET-UP

A. Acoustic Emission Detection:

1. Install acoustic emission transducer (e.g., Acoustic Emission 2514) on a flat surface machined on the side of a combustor using contact cement (or if signal is weak, a special impedance matching couplant can be used).
2. Patch transducer lead into input of preamplifier (e.g., Technology Corp. Model 802P-A) located adjacent to combustor.
3. Patch preamplifier into input of UHFAE Threshold Detector and Frequency to Voltage Converter (TD/FVC). (The Dunnegan Endevco 4001 can partially fulfill this task; however, it is not a true FVC.)
4. Patch output of TD/FVC into Channel 1 of digital oscilloscope.

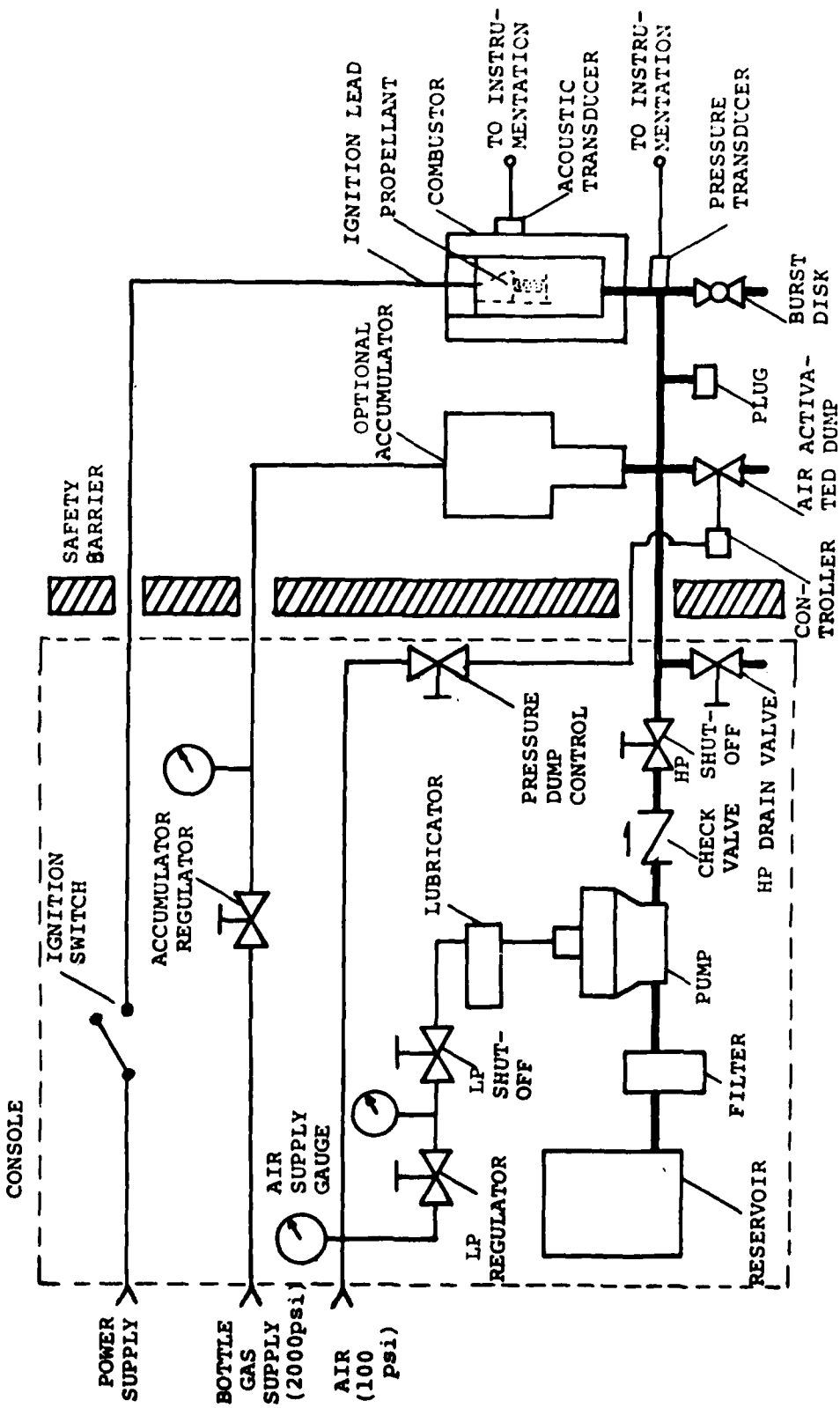
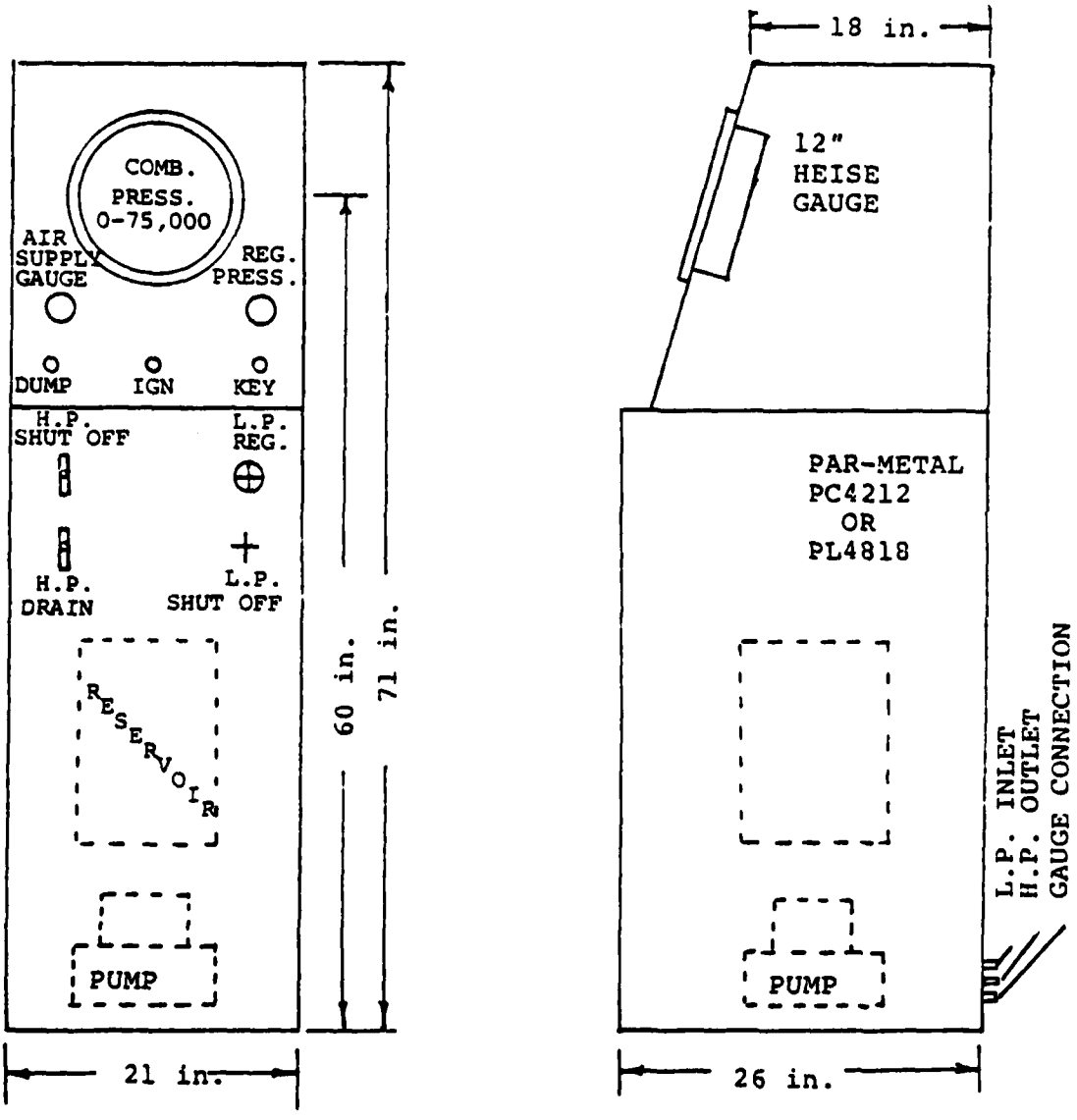


Fig. A-1 High Pressure combustion system uses a liquid for pressurization. The liquid is pressurized with an air-operated pump and the pressure can be maintained by using the accumulator.



FRONT PANELS: 1/8 inch STEEL
GAUGE PROTECTION: 1/2 inch PLEXIGLASS

Fig. A-2 Console to control hydraulic system.

5. Set threshold level on TD/FVC by simulating acoustic disturbance in combustor. As an option, the signal produced once the threshold is exceeded can be used in conjunction with the pre-trigger delay on digital oscilloscope to enable the data storage function.

B. Pressure Rise Instrumentation:

1. Install piezoelectric pressure transducer (e.g., Kistler 607C4) in fitting at base of combustor.
2. Patch transducer lead into input of charge amplifier (e.g., Kistler 504A).
3. Patch output of charge amplifier into Channel 2 of digital oscilloscope.
4. Set charge amplifier (e.g., Kistler 607C4/504A system typical settings: Index = 0.128; range = 50 (black), 500 psi/v; time constant = long).

C. Igniter Circuit:

1. Voltage: typically 14 VDC for 10 cm of Parr Fuse Wire No. 45C-10.
2. Trigger: If igniter circuit is to trigger (i.e., enable the data storage function) digital oscilloscope, connect lead from igniter to trigger input on digital oscilloscope. Alternatively, a threshold signal based on either the pressure signal or acoustic emission signal can be used in conjunction with a pre-trigger delay to enable the data storage function.

II. IGNITER PREPARATION

A. Cut a 10 cm length of nichrome wire (e.g., Parr Fuse Wire No. 45C-10).

B. Bend wire with needle nose pliers to a "W" - squeeze ends closed slightly and bend pigtail 90° 2/3 distance of loop width (W). Width of igniter should correspond to diameter of grain.

C. Mark hole for pigtails on cardboard disk and drill with 0.020 inch drill (disk punched on paper punch from 0.010 inch thick cardboard).
D. Insert igniter pigtails through holes in disk and bend wires 90° on other side.
E. Place drop of Duco Cement on wire and disk. Hold face down on polyethylene plastic for 30 seconds until dry.

III. MACHINING AND INHIBITING PROPELLANT GRAINS

A. Face both ends of grain by machining to desired length (e.g., 1.00 cm).
B. Clean out perforation with drill bit in pin vise.
C. Insert grain into inhibiting tool (rubber bulb and tygon tubing).
D. Dip into inhibitor and pull liquid through perforations. An inhibitor which was found to be successful is Gliddon Black Bituminous paint No. 8080-664-7105.
F. Remove from inhibiting tool, place end onto tape and inhibit outside surface.
G. Remove inhibitor from end to be ignited.

Comments on Machining Specimens:

An apparatus was developed to machine the propellant specimens to a prescribed length (within ± 0.025 mm) and to insure that the top and bottom surfaces are parallel (within ± 0.025 mm). A photograph of the mechanism is shown in Fig. A-3. The propellant specimen (i.e., the as-received multi-perforated grain) is held in the plastic holder. The plastic holder is mounted in the carriage which guides the specimen into the rotary cutter. Following the first pass through the cutter, the plastic holder (with specimen clamped in place) is turned over and then a second pass is made. Since the plastic holder is parallel sided and since the specimen is not removed from the plastic holder until both ends have been cut, a very good dimensional control is obtained. Length of the propellant specimen can be controlled to within ± 0.025 mm and the ends are

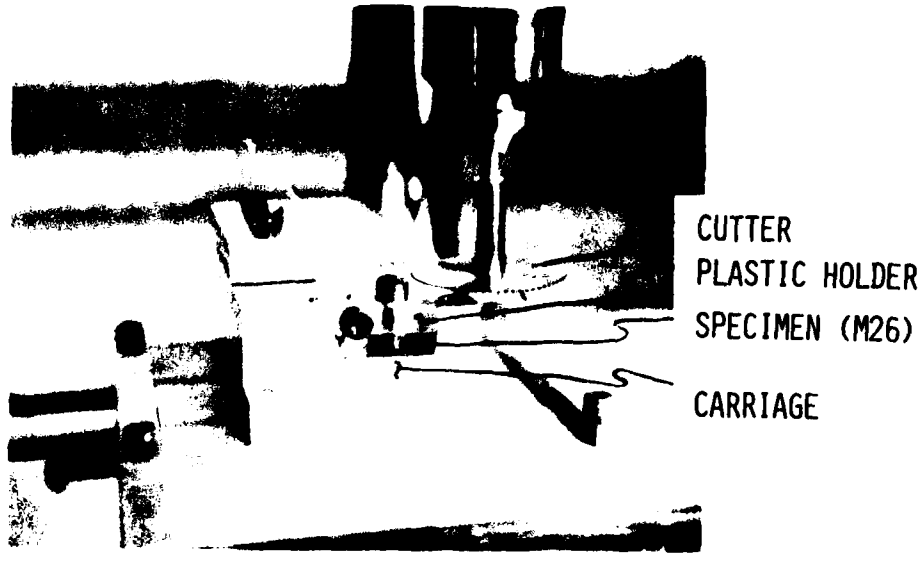


Fig. A-3 Apparatus to machine propellant specimens to a prescribed length and insure that top and bottom surfaces are parallel.

parallel to within ± 0.025 mm. In addition to producing specimens which have better dimensional control than was obtained by facing the ends using a lathe, the method takes about 1/5 the time required when a lathe is used and can be carried out by a relatively inexperienced operator.

Comments on Inhibiting Specimens:

Alternate methods of inhibiting the propellant specimens were examined. During the first part of the study, the inhibitor in the perforations was dried by a flow of N_2. It was found that this drying step is unnecessary and, in some cases, detrimental since it removed too much of the inhibitor. The majority of the tests were performed with uncured inhibitor in the perforations.

IV. PROPELLANT GRAIN MOUNTING IN HOLDER

(Typical configuration for ∿ 0.250" dia. grains)

A. Mount grain (inhibited side down) onto base plate with smear of zinc chromate putty.
B. Feed igniter wires through ring retainer and clip into igniter leads (alligator clips).
C. Trim excess igniter wire. Check hot lead to prevent shorting to ground.
D. If multiple specimens are used, repeat Steps A through D for each specimen.
E. Insert head into combustor.

V. PRESSURIZATION AND COMBUSTOR SYSTEM

A. Safety Precautions:
   1. Lock out igniter circuit prior to connecting igniter leads.
   2. No entry to combustor area when combustor is pressurized.
   3. Wear safety glasses when operating control console.
   4. Turn on exhaust fans before opening combustor at completion of run.

B. Instrumentation Set-Up (see previous section).

C. Pre-Run Checklist

1. Water level of reservoir in pump console.
2. Check oil level in pump lubricator glass bowl inside console.
3. Check water filter, mounted inside console, by removing bowl.
4. Drain air filter, mounted inside console, by opening valve at the bottom of bowl.
5. Check high pressure burst disk, mounted inside console for proper range.
6. Check regulated lab air burst disk, mounted inside console, for proper range.

NOTE: Do not change burst disks' range without authorization.

D. Water Temperature Conditioner

1. Fill storage reservoir of water temperature conditioner.
2. Set thermostatically-controlled heater to desired temperature.
3. Wait for water in reservoir to achieve desired temperature. Control to ± 0.3 K is readily obtainable.

E. Combustor Loading

1. Close "HP Drain" on console.

NOTE: Do not over-tighten any high pressure valves, as this will damage their seats. Pressure of thumb & forefinger is sufficient to seal these valves.

2. Check that the "O"-ring and back-up ring, for sealing the combustor cap, are in their proper position. (IMPORTANT: PRESSURIZING COMBUSTOR WITH THESE RINGS COCKED, WILL DESTROY "O"-RING AND BACK-UP RING.)
3. Check that residue screen is in position at bottom of combustor.

4. Fill combustor with temperature-conditioned water to desired level (normally to "O"-ring) with water hose from storage reservoir.
5. Insert thermostatically-controlled heater into liquid in the combustor to pre-condition the combustor body to desired temperature. Once this is accomplished, the large mass of the combustor will tend to maintain the desired temperature on subsequent refillings of temperature-conditioned water.
6. Measure and record water temperature.
7. Insert plug which contains propellant specimens by lowering straight down onto back-up ring and "O"-ring.
8. Install plug hold-down nut and tighten.
   IMPORTANT: ALIGNING MARKS ON NUT AND COMBUSTOR TOP MUST ALIGN. MIS-ALIGNMENT INDICATES "O"-RING AND BACK-UP RING ARE OUT OF POSITION.
9. Connect igniter leads after verifying that power switch is in the locked off position.
10. All personnel leave area containing combustor.

F. Pressurization of Combustor

1. Accumulator (optional)
   a) Close "accumulator bleed valve".
   b) Close "accumulator pressurization N_2 gas valve".
   c) Open N_2 bottle valve.
   d) Crack open "accumulator pressurization N_2 gas valve". Read accumulator pressure on "accumulator pressure N_2 gauge".
   e) Close "accumulator pressurization N_2 valve" at desired pressure.
   f) Close N_2 bottle valve.
2. Combustor
   a) Check "regulator" to make sure it is in zero position.

b) Open "low pressure (LP) shut off" on console.
c) Open "HP shut off" on console.
d) Turn "regulator" until pump is activated. Observe pressure increase and increase regulator until desired pressure is reached.
e) Turn off "HP shut-off valve".
f) Turn off "LP shut-off valve".

SYSTEM IS NOW READY FOR TEST.

G. Recycle for Next Test
1. Lock out ignition system.
2. Release pressure by opening "H.P. Drain" valve.
3. Remove plug and specimen holder assembly.
4. Check screen at bottom for residue.
5. a) Return to Step E.
b) If additional tests are not to be run, go to Step H.

H. Shut-down at End of Test Series.
1. Turn off all instrumentation and electrical systems.
2. Turn off main air supply.
3. Open "L.P. Shut Off" valve.
4. Open regulator to bleed off system pressure.
5. Accumulator (Optional)
a) N_2 supply bottle must be closed.
b) Open "accumulator bleed valve".
c) Open "accumulator pressurization N_2 gas" valve to bleed pressure.
6. Water Temperature Conditioner
a) Turn off power.
b) Drain, clean, and dry system.
7. Combustor
a) Drain, clean, and dry.
b) Spray with rust inhibitor.
c) Place grease on seal rings.

Comments on Accumulator.

The pressurization system includes an accumulator for the purpose of maintaining the chamber pressure nearly constant (i.e., ±0.5% of mean pressure) as the propellant specimens burn. When the apparatus was originally designed, the magnitude of the pressure rise was not known. After the initial series of experiments were performed, it was learned that the pressure use was generally less than 5% when specimens less than 2.0 g were burned. Accordingly, under such conditions, the accumulator is not required. It can be shown easily that reporting the burning rate at a mean pressure when the pressure rise is less than 5% retains the accuracy of the measurement to well within 0.1%.

The accumulator is a high-pressure, differential piston device. When the larger diameter section is pressurized with low pressure N_2 (i.e., up to 2000 psi), pressures up to 60,000 psi can be produced in the small diameter section. Since the volume in the larger diameter section is relatively large, small displacements in liquid on the high pressure side do not affect appreciably the pressure in the large diameter section. Thus, as the pressure builds up in the combustor, liquid is forced into the accumulator against a nearly constant force exerted by the low pressure side of the piston. The system functioned as designed and will be useful whenever large amounts of propellant (e.g., > 5 g) are burned.

VI. SUMMARY CHECK LIST FOR OPERATING HIGH-PRESSURE COMBUSTOR APPARATUS

PREPARE HEAD

IGNITER & PROPELLANT SPECIMENS.

LOAD COMBUSTOR

VENT VALVE OFF.
DC POWER OFF.
CHECK O-RING SEAL.
WATER FILLED AND TEMPERATURE CONDITIONED.
INSERT HEAD, RETAINING RING, PLUGS (ALIGN MARKS).
IGNITER HOOKUP - CHECK FOR GROUNDING AND CONTINUITY.

OPERATION

PUMP UP PRESSURE.
DC POWER TO IGNITER ON.
INSTRUMENTATION SET.
CHARGE AMPLIFIER GROUNDED.
FIRE.

DEPRESSURIZATION

DC POWER OFF.
REGULATOR BACK TO ZERO.
VENT OPEN (COMBUSTOR DRAIN)

DATA

PICTURE OF OSCILLOSCOPE DISPLAY IF REQUIRED.
ACOUSTIC EMISSION TIME-START STOP (ms).
PRESSURE TIME (TO PEAK) (ms).
PRESSURE RISE (VOLTS).

REPEAT CYCLE FOR NEXT RUN

SHUT DOWN

POWER OFF.
AIR PRESSURE OFF - BLEED.
WATER OFF.
COMBUSTOR WATER DRAINED - WIPE DRY AND INHIBIT.
TEMPERATURE CONDITIONER TURNED OFF.

APPENDIX B

REQUIREMENTS FOR BASIC

HIGH-PRESSURE COMBUSTOR COMPONENTS

Purpose of Apparatus

To burn a solid propellant under high pressure to determine its burning characteristics.

Equipment Description

A suitable enclosure to house a high-pressure pumping system with gauges and valves to pressurize a remotely located pressure vessel and a dump valve for pressure venting.

Specifications for High-Pressure Components

Maximum design pressure	80,000 psi
Maximum operating pressure	50,000 psi
Normal operating pressure	40,000 psi

Pumping System Components

Pump - Air operated to pump water to 50,000 psi output.

Gauge - 12 in. dial 0-75,000 psi, Tol. 0.1%, 750 divisions, 10 psi per division.

Gauge - Standard commercial 2 1/2" dial -- panel mounted for low pressure air system.

Reducing Regulator, panel mounted, capable of maintaining constant set pressure.

Hand Valves, high pressure to isolate pressure in combustor.

Lubricator & Air Filter for Air Pump - fittings, lines and hardware to remote combustor.

Combustor System

Pressure Vessel rated at 60,000 psi, inside dia. 3 in., Depth 10 in.

Dolly stand with wheels for supporting combustor.

Pressure venting valve - remote control.

Pressure Head - modified for 4 igniter leads.

Blow-out disk for overpressure protection set at less than 55,000 psi.

APPENDIX C

DATA ACQUISITION AND ANALYSIS SYSTEM

This appendix outlines three approaches for acquiring multi-specimen data and determining the burning time intervals:

1. Present method using a digital oscilloscope.
2. Microprocessor-based data acquisition and reduction system.
3. Dedicated multi-specimen timers.

The elements required for each system are shown in Figs. C-1, C-2, and C-3. The features of each system are given in Table C-1.

The microprocessor-based system is the most attractive approach, whether one or several systems are required. It combines the data storage features of the digital scope with the data analysis capability demonstrated using the large digital computers. This application is rather routine in terms of recent advances in single board computers and analog-to-digital converter modules. Systems of comparable complexity have been designed and implemented by personnel in our laboratory.

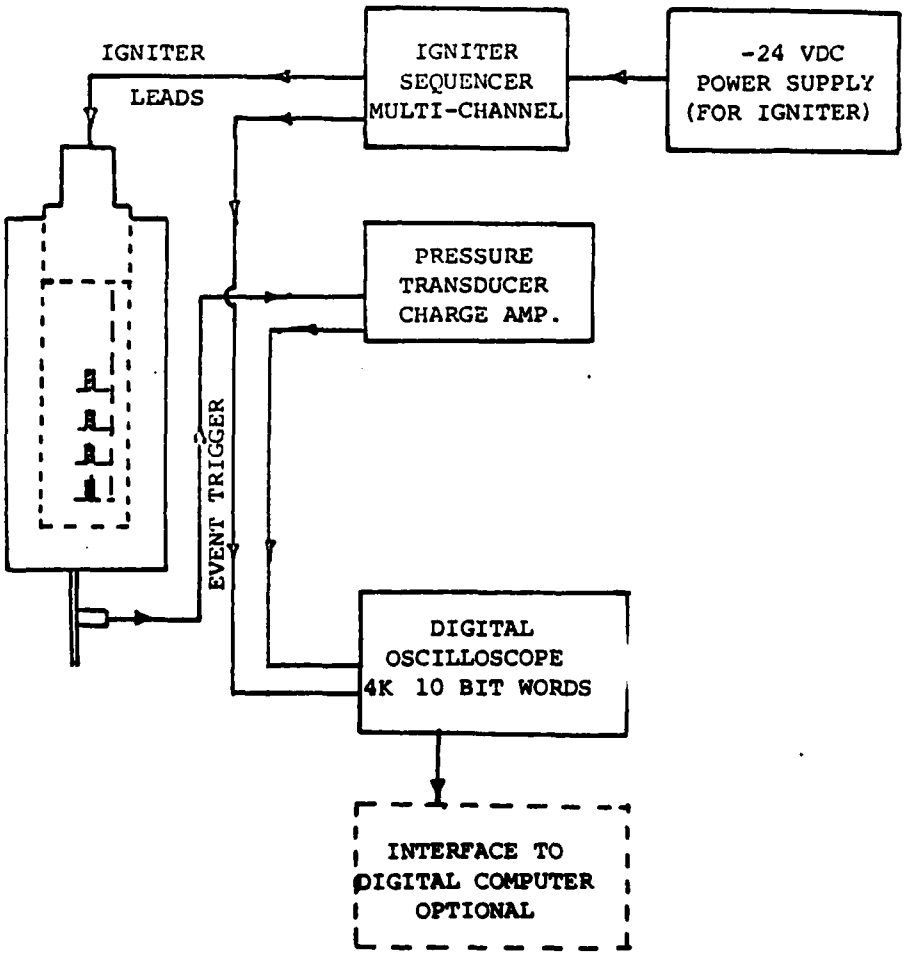


Fig. C-1 Instrumental Approach 1 -- Present method used digital oscilloscope with cursor readout of time and voltage. Burning time interval and mean pressure are read directly from display of digital oscilloscope.

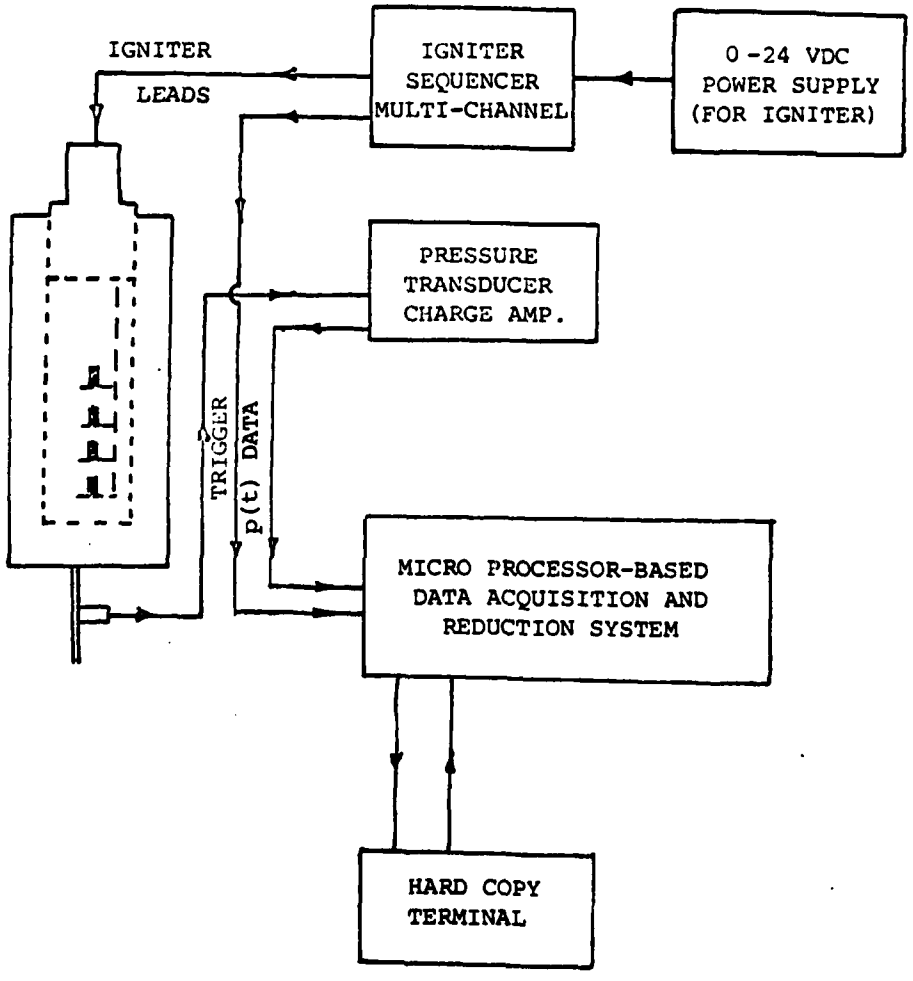


Fig. C-2 Instrumentation Approach 2 -- Microprocessor-based data acquisition and reduction system. Burning time intervals and mean pressure are calculated from the raw data and displayed on the hard copy terminal.

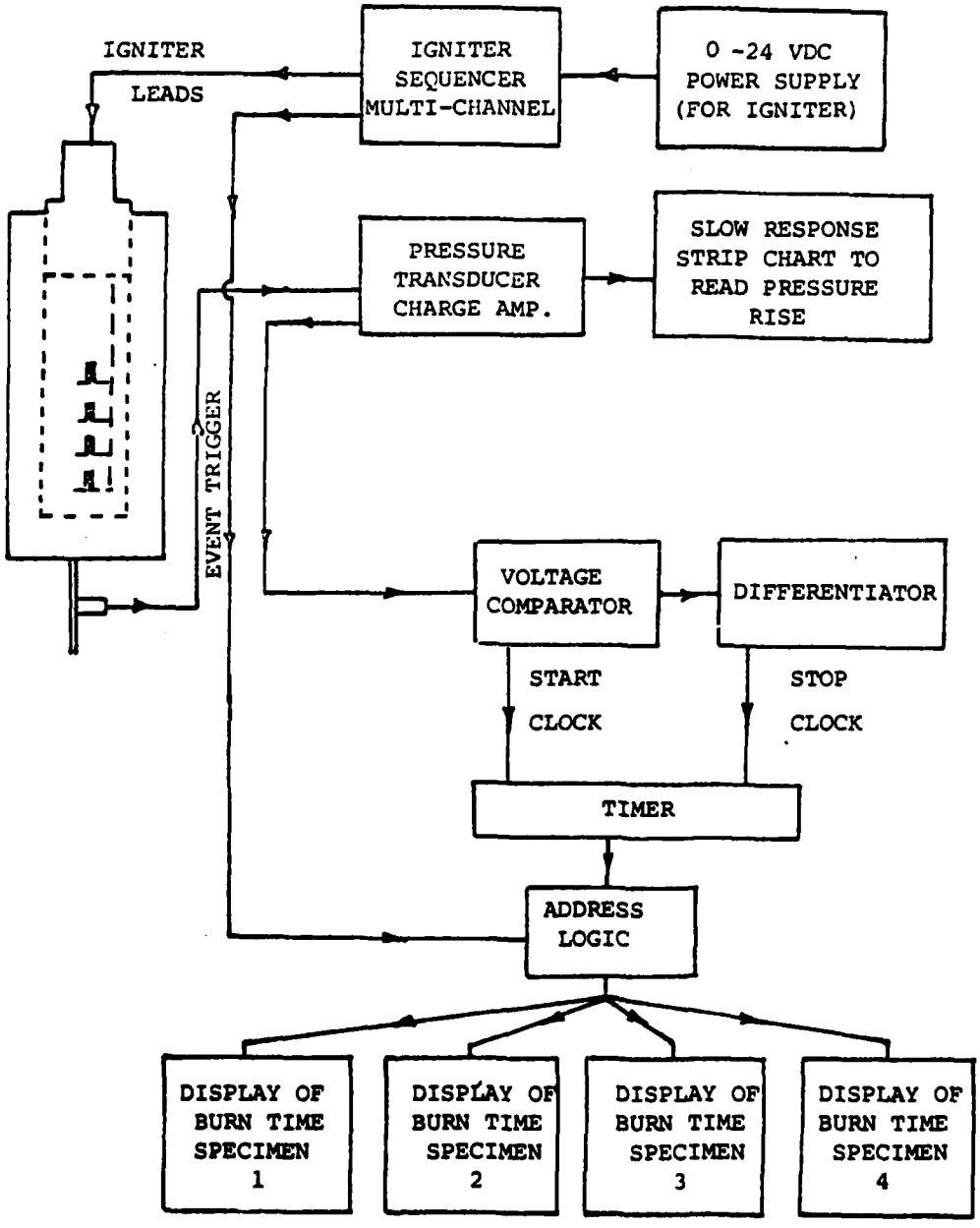


Fig. C-3 Instrumentation Approach 3 -- Dedicated multi-specimen timers. Burning times are displayed digitally for each specimen and mean pressure during each test is taken directly from slow response strip chart recorder.

Table C-1

APPROACHES TO DATA ACQUISITION AND ANALYSIS SYSTEMS

APPROACH	COMPONENTS REQUIRED	ADVANTAGES	DISADVANTAGES
Common to all approaches	1) Power supply for igniter: 12-24 VDC at 10 amps. 2) Igniter sequencer: multi-channel for multi-specimen tests. 3) Piezoelectric high-pressure transducer. 4) Charge amplifier for pressure transducer.		
1. Present method using digital oscilloscope	1) Digital oscilloscope with (a) 1000 words (10 to 12 bits) of memory for each specimen, and (b) cursor readout of voltages and times. 2) (Optional) Interface to digital computer for automated data analysis.	1) Works very well and proven by use in this study. 2) Demonstrated accuracy of better than 0.5%. 3) Minimum set-up time. 4) Burning rate irregularities can be identified readily by examining p vs t display.	1) Technical person needed to interpret ignition and burn. 2) Person operating unit has value judgments to make. 3) Digital oscilloscope cost is high.
2. Microprocessor-based data acquisition and reduction system.	1) Microprocessor (8 bit) with 4K of PROM for program and 1K of RAM for computations. 2) RAM storage for 1000 words (10 to 12 bits) for each specimen. 3) Analog to digital converter with 10 to 12 bit resolution and 10K word/sec sampling rate. 4) Hard copy terminal. 5) (Optional) Digital-to-analog display of p vs t data.	1) Operator judgment optional. 2) Can be operated with minimum training. 3) Data reduction steps can be varied by program changes or program options. 4) Second unit cost less than cost of digital oscilloscope. 5) (Optional) Ignition sequencing can be under microprocessor control. 6) (Optional) Data can be saved for further analysis.	1) Initial unit requires that special purpose computer program be written and checked out.
3. Dedicated multi-specimen timer.	1) Analog circuitry to recognize ignition and burnout times. 2) Address logic to select times and event. 3) Individual timers for each specimen. 4) Strip chart to record pressure rise (slow speed, inexpensive unit).	1) Lowest second unit cost. 2) Simplest to operate. 3) Direct readout of burning interval.	1) Less precise and least accurate system $\sim \pm 1.0\%$. 2) No operator judgment possible. 3) Setting up threshold levels requires calibration tests.